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# Role of Rogue Droplet Combustion in Hazardous Waste Incineration

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# THE ROLE OF ROGUE DROPLET COMBUSTION IN HAZARDOUS WASTE INCINERATION

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# ABSTRACT

In the incineration of liquid hazardous wastes, atomization quality may limit destruction efficiency. Large, non-mean droplets in a fuel spray can pass through the flame zone prior to complete evaporation, and may subsequently fail to burn completely due to insufficient temperature and/or flame radicals. A study was conducted to develop a predictive understanding of individual droplet trajectories in turbulent diffusion flames.

The influence of droplet spacing on the drag coefficient of individual drops injected into a quiescent environment has been determined through measurements of trajectories of single monodisperse, non-evaporating droplet streams. Droplet size, velocity, and spacing were varied, yielding initial Reynolds numbers (Re) ranging from 90 to 290 and initial droplet spacing to diameter ratios (L/D) ranging from 1.7 to 1700. Data from 10 trajectories were correlated using asymptotic forms for $C_D$ as follows:

$$\{C_D\ (Re,\ L/D)\}^{-n} = \{C_D^0\ (Re,\ L/D)\}^{-n} + \{C_D^\infty\ (Re)\}^{-n}$$

where $C_D^0 = C_{ROD}\ (Re) + aRe^b\ \{L/D-1\}$ and is the asymptotic form for $C_D$ as $L/D \dashrightarrow 1$, while $C_D^\infty$ is that for $C_D$ as $L/D \dashrightarrow \infty$. A trajectory model containing the local drag coefficient was fit to the experimental data by a non-linear regression, yielding the following values for the empirical parameters: n = 0.7071, a = 34.80, and b = -1.009. The resulting model with this drag coefficient formulation was then able to predict 4 additional measured trajectories and 39 additional measured trajectory endpoints with acceptable accuracy. Thus, the influence of droplet spacing on the local drag coefficient of a single droplet has been quantified.

A numerical model has been developed to predict the ballistics of an isolated burning droplet. This model includes the effects of droplet interaction on drag and evaporation rate, and turbulence effects on droplet penetration into the combustion environment. Experiments on a laminar flow flat-flame burner, and a 100 kW swirling, turbulent combustor have been conducted to calibrate the droplet ballistics model. Experimental results have shown that the droplet penetration increases with increasing droplet initial size, initial velocity, and decreases with increasing initial spacing. Model predictions on droplet penetration are very close to experimental findings except for the case of changing initial spacing of droplets in a stream.

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16. ABSTRACT

The report gives results of a study to develop a predictive understanding of individual droplet trajectories in turbulent diffusion flames. In the incineration of liquid hazardous wastes, atomization quality may limit destruction efficiency. Large, nonmean droplets in a fuel spray can pass through the flame zone prior to complete evaporation, and may subsequently fail to burn completely due to insufficient temperature and/or flame radicals. The influence of droplet spacing on the drag coefficient of individual drops injected into a quiescent environment has been determined by measuring trajectories of single monodisperse, nonevaporating droplet streams. Droplet size, velocity, and spacing were varied, yielding initial Reynolds numbers of 90-290 and initial droplet spacing to diameter ratios of 1.7-1700. Data from 10 trajectories were correlated using asymptotic forms for drag coefficient. A trajectory model containing the local drag coefficient was fit to the experimental data by a nonlinear regression. The resulting model was then able to predict 4 additional measured trajectories and 39 additional measured trajectory endpoints with acceptable accuracy. Thus, the influence of droplet spacing on the local drag coefficient of a single droplet has been quantified. Predictions of model penetration are very close to experimental findings, except for changing initial spacing of droplets.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group | |
|---|---|---|---|---|
| Pollution | Trajectories | Pollution Control | 13B | 19D |
| Drops (Liquids) | Flames | Stationary Sources | 07D | |
| Atomizing | Turbulent Diffusion | Hazardous Liquid Waste | 13H, 07A | |
| Combustion | Waste Disposal | | 21B | |
| Wastes | | | 14G | |
| Toxicity | | | 06T | |

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## GLOSSARY

| | |
|---|---|
| $a_x$ | Horizontal acceleration, $m/s^2$ |
| $a_y$ | Vertical acceleration, $m/s^2$ |
| a | Parameter defined by Equation (3-3) |
| A | Area of droplet cross-section [$= \pi D^2/4$], $m^2$ |
| b | Parameter defined by Equation (3-3) |
| $C_D$ | Instantaneous drag coefficient on a droplet |
| $C_D$ | Asymptotic form for $C_D$ as $L/D > 1$ |
| $C_D$ | Drag coefficient for an isolated sphere |
| $C_{ROD}$ | Friction drag coefficient for a long rod |
| D | Droplet diameter, m |
| f | Frequency of vibration, Hz |
| $F_x$ | Horizontal force [$= ma_x$], N |
| $F_y$ | Vertical force [$= ma_y$], N |
| g | Acceleration to gravity, $m/s^2$ |
| L | Distance between centers of two droplet neighbors, m |
| $L^o$ | Initial distance between droplet [$= L_s N$], m |
| $L_s$ | Distance between droplets of unseparated droplet stream, m |
| m | Droplet mass, kg |
| n | Parameter defined by Equation (3-4) |
| N | Number of frequency divisions |
| p | Horizontal velocity [$= dx/dt$], m/s |
| q | Vertical velocity [$= dy/dt$], m/s |
| $\dot{q}$ | Flow rate of droplet stream, ℓ/s |
| t | Time, s |
| T | Droplet temperature, °C |
| $T_g$ | Gas temperature, °C |
| Re | Reynolds number [$= \rho_d VD/\mu_a$] |

## GLOSSARY (continued)

| | |
|---|---|
| $Re^{\circ}$ | Initial Reynolds number |
| $V$ | Magnitude of droplet velocity $[= (p^2 + q^2)^{1/2}]$, m/s |
| $V^{\circ}$ | Initial droplet velocity, m/s |
| $V_g$ | Gas velocity, m/s |
| $x$ | Horizontal coordinate, m |
| $y$ | Vertical coordinate, m |
| $\rho_a$ | Density of air, kg/m$^3$ |
| $\rho_d$ | Density of droplet, kg/m$^3$ |
| $\theta$ | Angle between trajectory and horizontal axis |

## EXECUTIVE SUMMARY

Of the hazardous organic wastes produced in the U.S., about 75% are liquids or dissolved in liquids. With landfill disposal of these wastes becoming increasingly unpopular due to growing public concern and increased levels of hazardous waste production, thermal destruction is being considered as an alternative disposal method. Successful incineration requires that flame radicals and high temperatures be combined in such a way that the principal organic hazardous components (POHCs) of the feed waste are destroyed and that the formation of products of incomplete combustion (PICs), which may be as hazardous as, or even more hazardous than, the original POHCs, are minimized. Proper spray atomization provides the necessary dispersion of liquid fuel and waste into the oxidizer to avoid incinerator failure by inadequate mixing. Fuel spray nozzles degrade with use and must be replaced periodically. Therefore, there is a need to understand and quantify how atomization parameters limit liquid waste incineration so that a sound rationale for selecting and replacing spray nozzles can be defined.

Four group combustion modes of a fuel droplet cloud have been identified, with single droplet combustion being applicable in practice to only a very limited number of special situations. Such a special situation, however, can arise during the incineration of liquid hazardous wastes, where droplets with large diameters (as much as an order of magnitude larger than the mean) congregate at the outer edge of fuel spray cones. One or more of these large, errant droplets may individually pass through, or bypass, the main flame zone and lead to a failure mode in the incinerator. For example, bypassing of as few as one drop out of 10 million drops can lead to failure to meet a destruction removal efficiency (DRE) in excess of 99.99%, as is required by law.

Motivation for this study lies, therefore, in the need to predict single, non-mean droplet trajectories in a turbulent flame zone. To this end, experiments have been conducted 1) to determine minimum requirements of a model that successfully predicts measured trajectories of single monodisperse droplet streams in three-dimensional turbulent diffusion flames, and 2) to relate droplet penetration distance to potential incinerator failure modes.

A semi-empirical numerical model has been developed for predicting the ballistics of burning droplet streams in turbulent diffusion flames. An important input to this model is a proper representation of the drag coefficient on a nonevaporating droplet in a stream.

### Drag Coefficient

While much information is available on the relationship of the drag coefficient, $C_D$, of an isolated sphere to Reynolds number, Re, little is available on the dependence of $C_D$ on Re and droplet spacing, nondimensionalized by droplet diameter, D, as L/D. As droplet spacing is reduced, drag is reduced due to wake effects. For large droplet spacings, when droplets cease to interact, the drag coefficient, $C_D^{\infty}$, for each one is that of an isolated sphere, and is only a function of Re. For the slightly distorted droplets formed by a vibrating capillary droplet generator, the relation of Lambiris and Combs[19] is recommended:

$$\begin{aligned} C_D^{\infty}(Re) &= 27\ Re^{-0.84}, && D < Re < 80 \\ &= 0.27\ Re^{0.217}, && 80 < Re < 10^4 \\ &= 2, && Re < 10^4 \end{aligned} \tag{1}$$

In the other extreme, as droplet spacing approaches the droplet diameter, the drag coefficient may be assumed to approach the friction drag coefficient of a long rod, which can be calculated from the theory of Glauert and Lighthill.[21] A general form for the asymptotic form for the drag coefficient, $C_D^{O}$, of a sphere as L/D approaches unity is obtained by a Taylor expansion about L/D = 1; thus, $C_D^{O}$ is hypothesized to be:

$$C_D^{O}(Re,\ L/D) = 0.755/Re + aRe^{b}\ [L/D-1] \tag{2}$$

where a and b are parameters to be determined from experiment. The factor $[aRe^{b}]$ multiplying $[L/D-1]$ is hypothesized to be a function of Reynolds number, since the extent of droplet interaction as L/D approaches 1 will depend on Re, the latter quantity determining the length of wake behind each droplet. An effective and universal technique to correlate data, obtained between regions of validity for the asymptotic forms for $C_D$ as L/D-->1 and L/D-->∞, is to use the asymptotic expansion formula developed by Churchill[24]:

$$[C_D(Re,L/D]^{-n} = [C_D(Re,L/D)]^{-n} + [C_D^{\infty}(Re)]^{-n} \tag{3}$$

where n is a parameter to be obtained by experiment.

## Trajectory Model

A simple, numerical model has been developed for predicting the ballistics of an isolated burning droplet. This model includes effects of droplet interaction on drag and evaporation rate, evaporation effects on drag, and turbulence effects on penetration. The model is used to solve the uncoupled equations of droplet motion in a Lagrangian framework. A three-dimensional grid structure is established for specifying the background gas velocity ($v_g$), temperature ($T_g$), and chemical speciation. Calculations are terminated when the droplet exits the computational domain.

## EXPERIMENTAL METHODS AND RESULTS

The objectives of this study were 1) to measure and predict the three-dimensional trajectories of single monodisperse droplet streams in turbulent diffusion flames, and 2) to study the relation of these trajectories with droplet incineration effectiveness.

The droplet generator is a vibrating orifice device with ancillary electronics to facilitate droplet spacing variation. Initial droplet diameter and spacing were measured via strobe photography. Initial droplet velocity was calculated from the vibrator frequency setting. The fluid tested, chosen on the basis of conductivity (for electrostatic charging and deflection) and viscosity (for droplet formation), was a mixture of 80% (by volume) Shell Oil Company fuel additive ASA-3, comprised mostly of xylene ($C_8H_{10}$), and 20% distillate fuel oil.

To determine droplet spacing effects on the nonevaporating droplet drag coefficient, trajectory experiments were conducted in the cold flow, quiescent environment within an observation tunnel. Empirical parameters a, b, and n (Equations 2 and 3) were evaluated.

Parameters a, b, and n were estimated using data from 10 full trajectories. Nonlinear regression for parameter estimation was accomplished using a modified Marquardt[27] algorithm, which is based on a multidimensional search in parameter space for the minimum value of a sum of squares functional measuring deviation from the data. The least squares parameter estimates were: $a = 34.8$, $b = -1.009$, and $n = 0.7072$.

Measured and predicted trajectory endpoints are shown in Figure ES-1 for the 10 trajectories in regression and for 39 additional trajectories.

Two-dimensional laminar flow experiments in a bench-scale flat-flame burner were then conducted to calibrate the model, allowing minimum model requirements to be determined without the complexities of three dimensions and turbulence. Trajectories of nonburning and burning droplets were measured to test the model in this aerodynamically simple environment. These results, shown in Figures ES-2, ES-3, and ES-4, demonstrate that droplet interaction effects on evaporation rate and evaporation effects on drag are important model requirements. An important result from these two-dimensional laminar flow experiments was the determination of the value of $B_3$, the mass transfer coefficient of the third phase in the 3 phase burning liquid. A value of 0.1 for $B_3$ made model predictions of the droplet burnout point to be in fair agreement with the experimental observations.

Three-dimensional turbulent diffusion flame experiments were conducted on an 100 kW combustor. In baseline tests without droplet injection the combustion gas flow field was characterized in terms of temperature and velocity.

Droplet trajectories were measured with the aid of high speed photography. Droplet destruction efficiency was determined by measuring the increased levels of exhaust unburned hydrocarbons (UHC, or surrogate POHC) and carbon monoxide (CO, or PIC) due to droplet injection. These emission measurements were taken from the stack where the combustion gases are well mixed. Flame ionization was used to detect UHC, and an infrared instrument was used for CO measurement. A removable water-cooled coil for quenching the combustion gases was inserted, resulting in a bulk gas residence time of 0.6 s before quenching.

Droplet trajectories were observed for a variety of initial droplet stream conditions, including variation in droplet size, velocity, spacing, and injection angle. Finally, droplet incineration was measured with the quench coil inserted.

The experimentally measured droplet axial penetration and the model predictions are given in Table ES-1. Closely spaced droplets penetrated

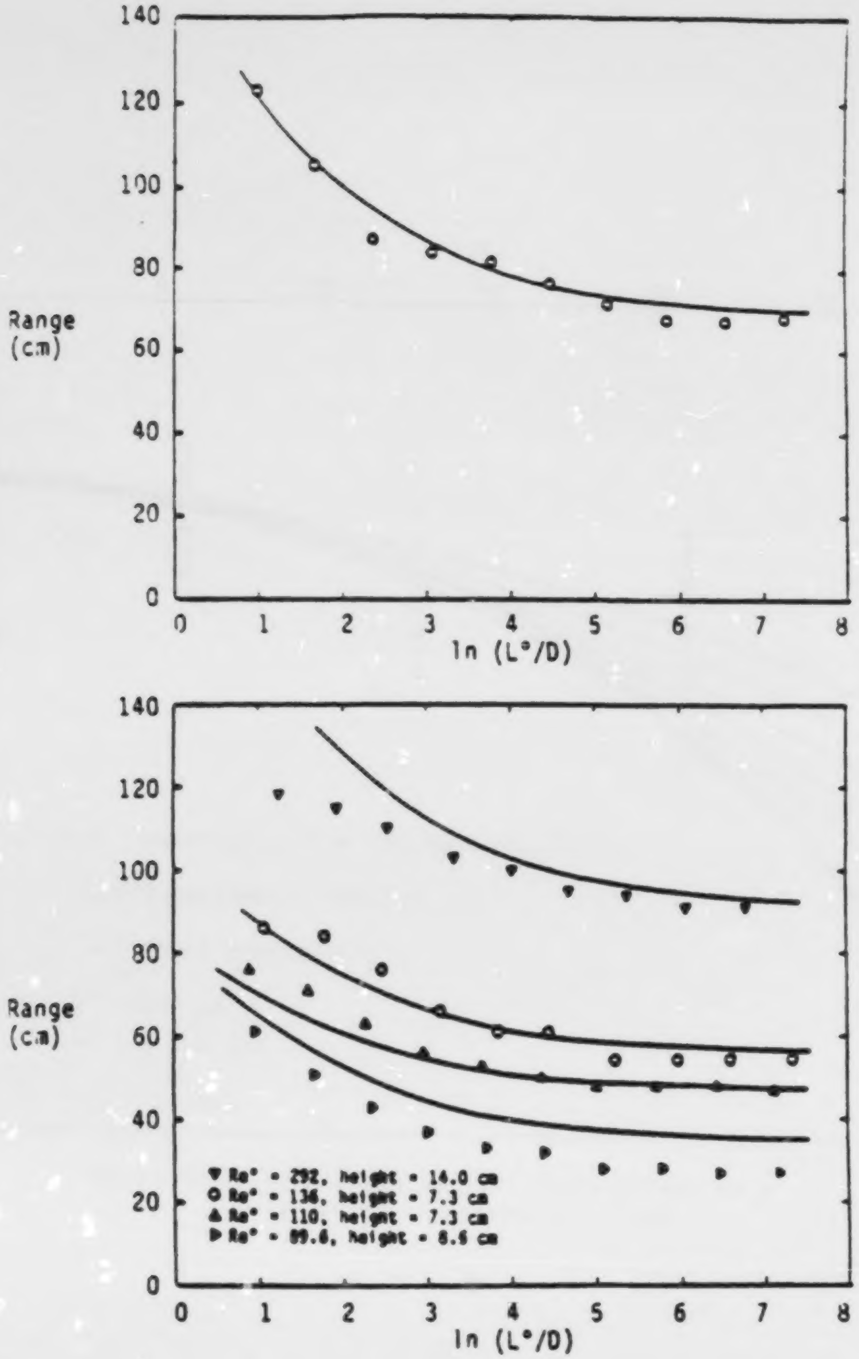


Figure ES-1. Droplet trajectory endpoints. Points represent measured trajectory endpoints; lines are model results. Results from the best-fit non-linear regression of 10 full trajectories at Re° = 211, with the endpoint being the horizontal distance (range) that a droplet travels while falling a vertical distance (height) of 11.7 cm, are shown in the top plot. Model predictions of 39 more trajectory endpoints are shown in the bottom plot.

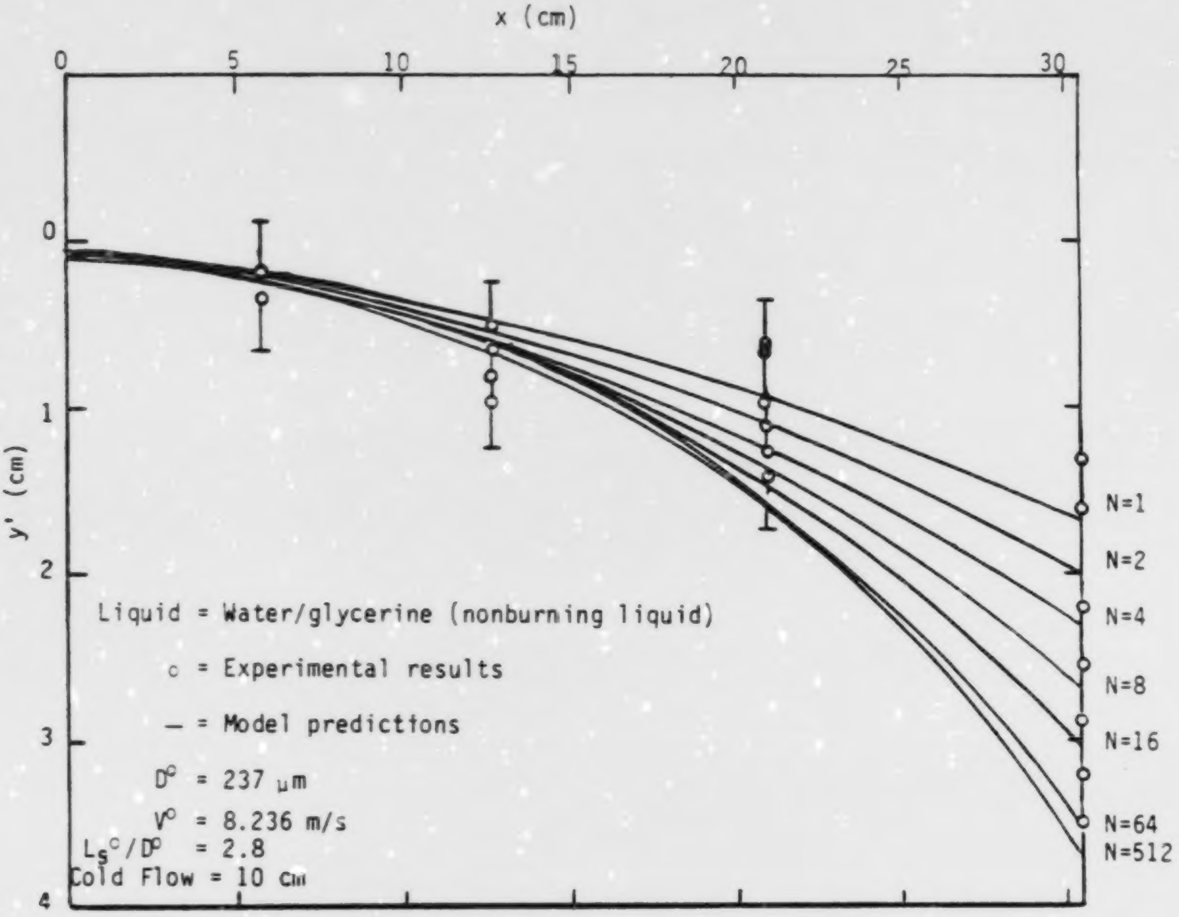


Figure ES-2. Nonburning droplet trajectories in a laminar two dimensional flame

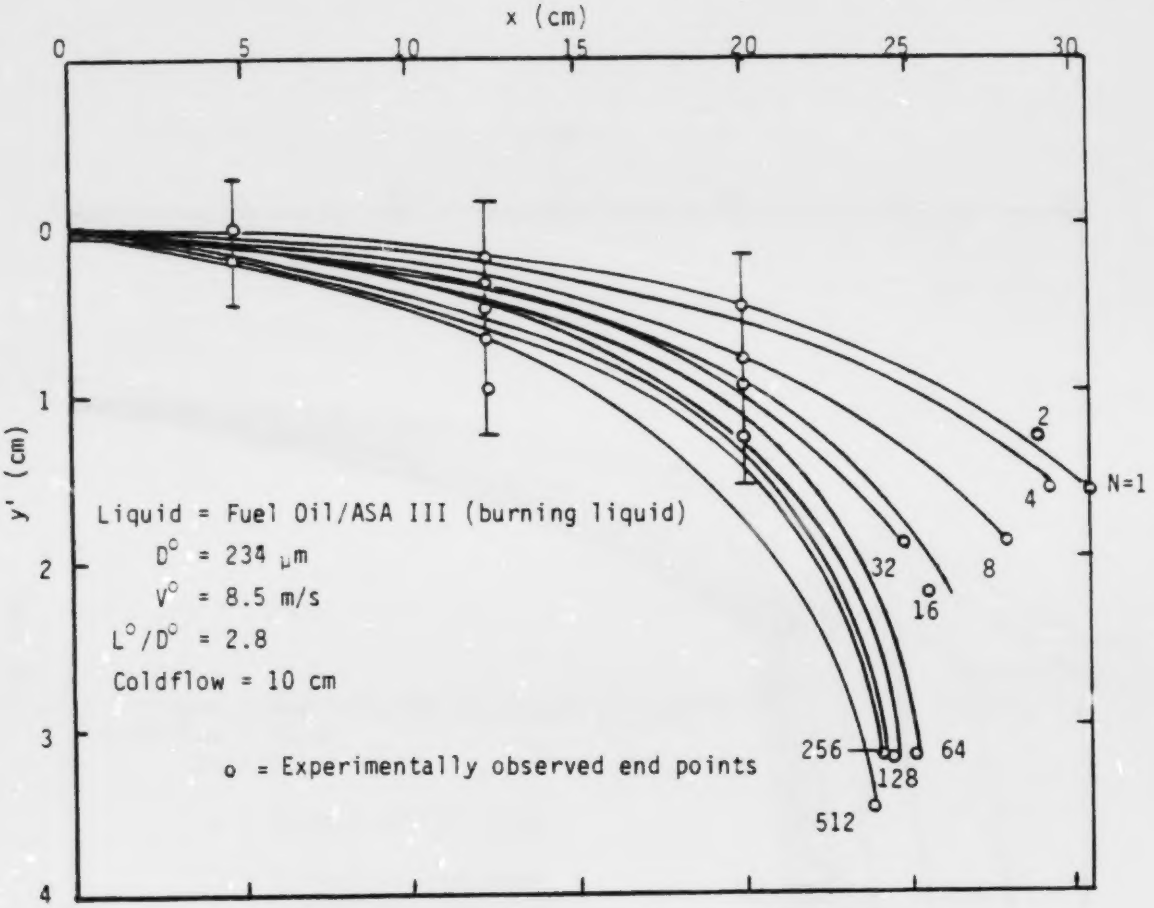


Figure ES-3. Experimental results for trajectory measurements of various differently spaced droplet streams in a laminar two dimensional flame.

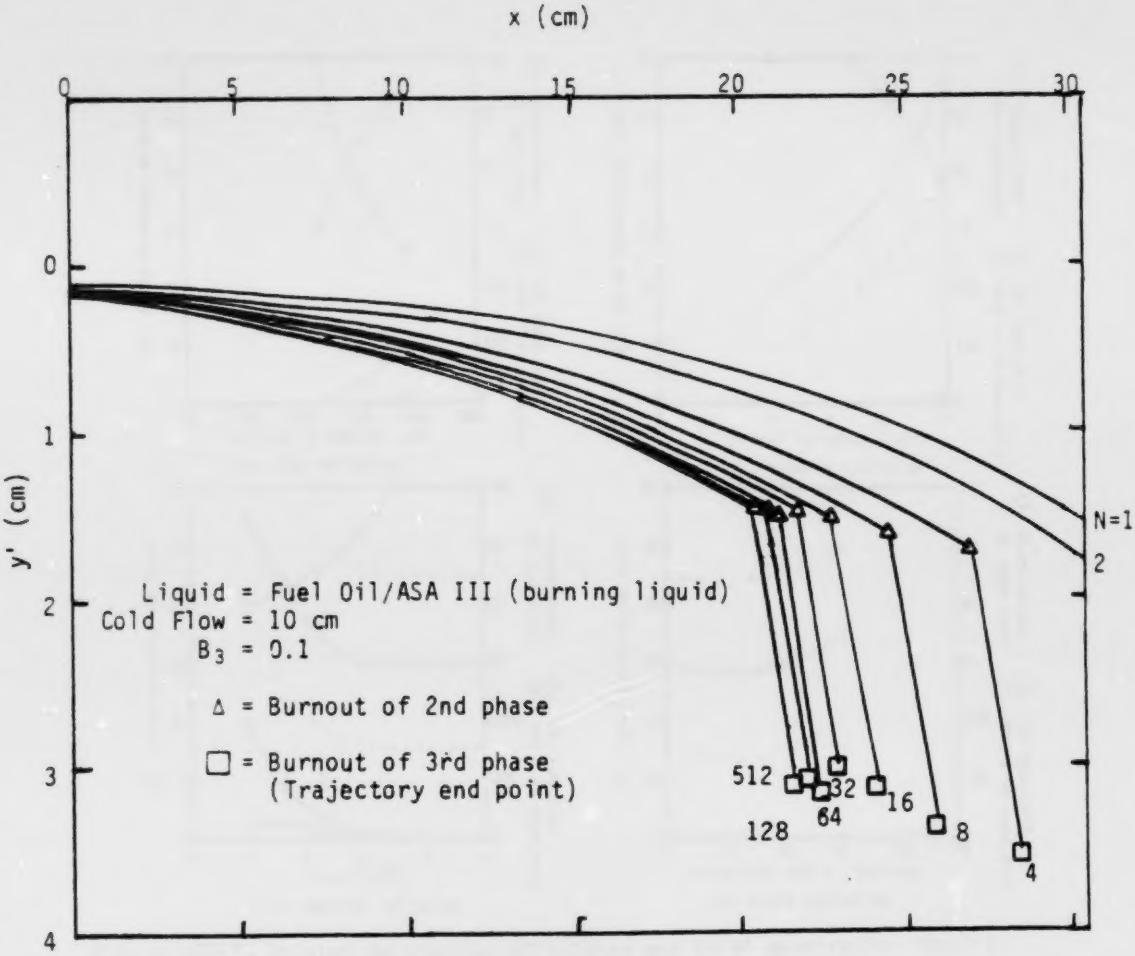
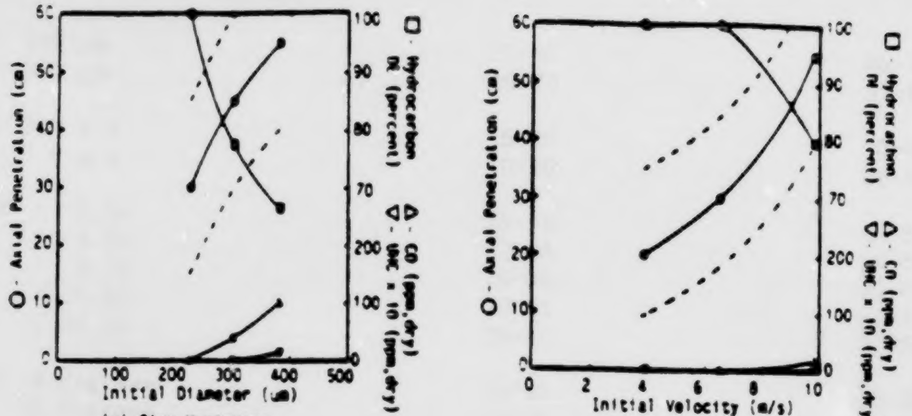
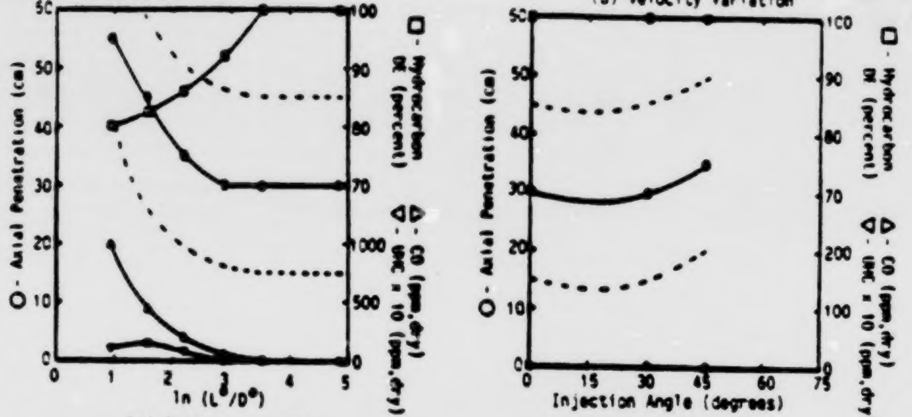


Figure ES-4. Model predictions for trajectories of various differently spaced droplet streams in a laminar two dimensional flame.



(a) Size Variation

(b) Velocity variation



(c) Spacing variation

(d) Angle variation

Figure ES-5. Droplet destruction efficiency and axial penetration results.

TABLE ES-1. MEASURED DROPLET AXIAL PENETRATION IN A THREE-DIMENSIONAL TURBULENT DIFFUSION FLAME AND CORRESPONDING MODEL PREDICTIONS

| Input Test Condition | Experiment Axial Penetration (cm) | Model Axial Penetration (cm) |
|---|---|---|
| Nominal: $D^\circ = 234\ \mu m$<br>$V^\circ = 6.2$ m.s<br>$L^\circ/D^\circ = 131$<br>$\theta^\circ = 30$ degrees | 20-45 | 30-55 |
| $D^\circ = 306\ \mu m$ | 35-60 | 40-64 |
| $= 371\ \mu m$ | 45-70 | 53-68 |
| $V^\circ = 3.8$ m/s | 15-25 | 20-42 |
| $= 7.4$ m/s | 30-60 | 32-65 |
| $L^\circ/D^\circ = 2.54$ | 35-75 | 32-59 |
| $= 4.80$ | 30-65 | 32-59 |
| $= 9.10$ | 20-55 | 31-59 |
| $= 17.50$ | 20-45 | 31-59 |
| $= 34.00$ | 20-40 | 31-59 |
| $\theta^\circ = 0$ degrees | 20-45 | 20-55 |
| $= 45$ degrees | 20-50 | 20-55 |

farther than isolated droplets. Little effect of spacing was observed for values greater than 10 diameters. Axial penetration distance roughly doubled with a doubling of initial velocity. Droplet penetration increased as droplet diameter increased, as well. Little change in axial penetration was observed for isolated droplet injection at 0 and 45 degrees. As shown in the table, these trends are also predicted by the model when run using $B_3 = 0.1$ obtained earlier in two-dimensional laminar flow experiments. However, the model needs to be improved to predict droplet spacing effects on axial penetration a little better.

Tests were conducted with the water-cooled coil inserted downstream of the Type-C flame to quench the combustion gases and measure droplet incineration. Combustion gases were extracted from the stack, with emissions analyzed with and without droplet injection. Droplet destruction efficiency (DE) was calculated as the mass of carbon emitted as CO and UHC divided by the mass of carbon injected.

Droplet incineration results are shown in Figure ES-5. The previously measured mean axial penetration is also shown, with dashed lines representing the range of droplet trajectories. These data indicate that droplet destruction efficiency is related inversely to droplet penetration, which has been shown to depend on droplet atomization properties. Thus, predicting droplet ballistics may be one tool for anticipating incinerator failure modes due to poor atomization.

## CONCLUSIONS

Large droplet penetration of the flame zone has been observed as a function of droplet atomization parameters in tests with single monodisperse droplet streams injected into turbulent diffusion flames. The incomplete incineration of these hydrocarbon droplets has been approximated by measuring CO and UHC emissions, and a strong correlation with droplet penetration has been observed. The short burning distances and relatively long trajectories prior to ignition exhibited suggest that droplet aerodynamics prior to ignition is of primary importance in understanding and predicting DRE.

# SECTION 1

# INTRODUCTION AND BACKGROUND

With landfill disposal of hazardous wastes becoming increasingly unacceptable due to growing public concern over air and water contamination and increased hazardous waste production, thermal destruction of the organic component (a significant fraction) of these wastes is being considered as an alternative disposal method. Successful incineration requires that flame radicals and high temperatures be combined in such a way that the principal organic hazardous constituents (POHC's) of feed waste are combusted with a 99.99 percent or greater destruction and removal efficiency (DRE). Further, environmentally safe incineration requires that products of incomplete combustion (PIC's), which may be as hazardous or even more hazardous than the original POHC's, must be minimized. Because the consequences of incomplete incineration to a community's environment and health are so great, prediction of incineration effectiveness is essential prior to implementation.

Of the hazardous organic wastes produced in the U. S. about 75 percent are liquids or dissolved in liquids. In liquid spray combustion, the physical processes of atomization and droplet aerodynamics and the thermal and chemical processes of thermodynamics, heat transfer and kinetics are coupled, resulting in a complex set of governing equations for droplet motion and incineration.

Liquid spray combustion or droplet burning is fundamental to many combustion systems and has received much attention.(1-3) Semi-empirical solutions have been derived for both single droplet and group combustion by assuming idealized combustion environments.(4,5) Thus far, however, these models, with their simplified (external) fluid mechanics, have been unsuccessful in predicting critical pollutant emissions from practical combustors.(6)

The combustion of liquid fuels in most practical combustors is dominated largely by the overall dynamics of the fuel spray and by the combustion of particle clouds, rather than by the trajectories of single droplets.(7) However, in the incineration of liquid hazardous wastes, the situation is different. Here, a destruction removal efficiency in excess of 99.99 percent is required, and the penetration or bypassing of the flame zone of a very few individual droplets can lead to a failure mode. For example, the escape of one rogue 300 μm droplet out of 2 million droplets of a mean diameter of 50 μm will lead to a DRE of less than 99.99 percent, and, thus to a failure of the incinerator. Measurements of droplet size distributions in various fuel sprays have found diameters of 100 to 500 μm, which is an order of magnitude larger than the mean.(8) These rogue droplets tend to concentrate at the outer edge of the spray core. The subsequent fate of these individual droplets is then of paramount importance.

It has been found that physical processes can dominate chemical kinetic effects during large droplet combustion, resulting in droplet penetration of the flame zone.(9,10) A study was begun at the U.S. Environmental Protection Agency's (EPA) Air and Energy Engineering Research Laboratory (AEERL) located in Research Triangle Park, NC to measure and predict the trajectories of single, monodisperse droplet streams in turbulent, swirling combustion flow fields as a function of the droplet atomization parameters of size, velocity, spacing, and injection angle and correlate the trajectories to droplets' incineration. Acurex Corporation was contracted by the EPA/AEERL to conduct experiments and report on the results. This final report documents the activities of the project from January 1984 through May 1987.

The primary objective of characterizing droplets' trajectory and incineration in hot swirling, turbulent flows was broken down into two subtasks:

(1) To characterize the drag on a droplet as a function of Reynolds number (based on the droplet) and spacing between the droplet under consideration and any neighboring droplet;

(2) To measure and predict the trajectories of droplets, at varying injection conditions, in a three dimensional, swirling, turbulent and combusting flow field.

Each of the above sub-tasks was accomplished by carrying out a series of carefully performed experiments. These experiments and their related results are described in Sections 3, 4, and 5, respectively.

## SECTION 2

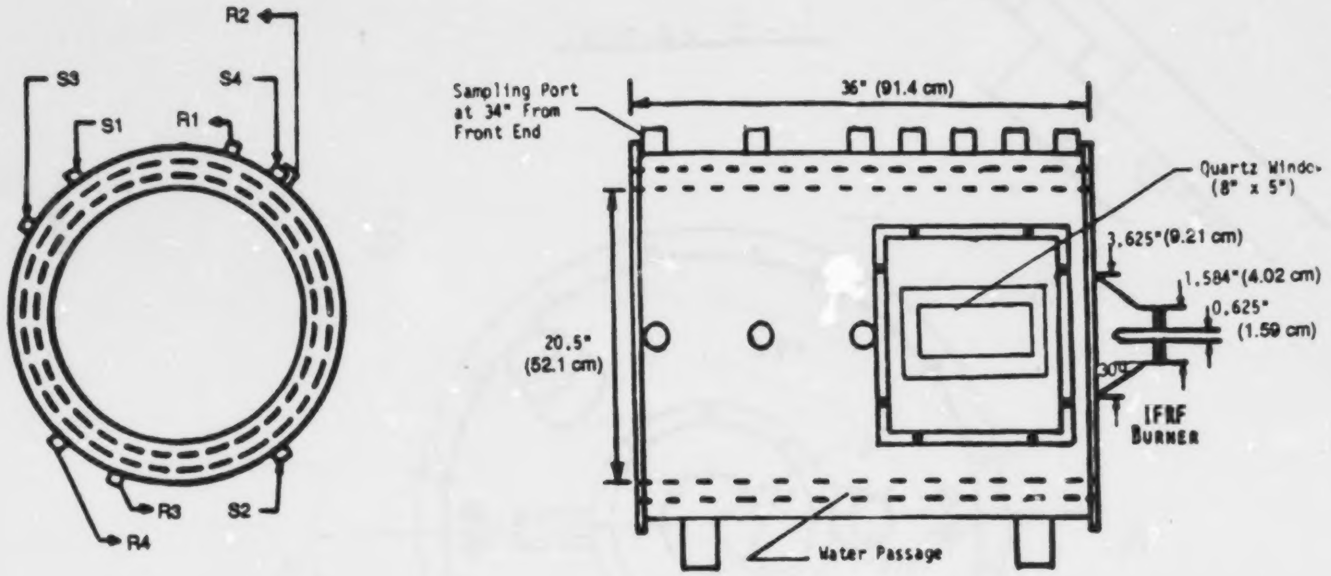
## EXPERIMENTAL APPARATUS

The primary hardware components used in the experimental program were the Rainbow Furnace, the flat-flame burner, and the droplet generator. Each of these is described in the following sections.

### 2.1 THE RAINBOW FURNACE

The 100 kW versatile bench-scale combustor is described in detail in (11). To accomplish the objectives of this program, it was necessary to be able to visualize the flame and the droplet trajectories inside the combustor and to be able to inject droplets into the furnace. These features were incorporated into the furnace by fitting the furnace with a near-burner module and a front-end with a slot for droplet injection. The near-burner module shown in Figure 2-1 is a water-cooled cylinder fitted with multiple sampling ports for in-flame measurements; in addition, this module also incorporates a large quartz window on one side for near flame visualization studies. The burner front-end, shown in Figure 2-2, is also water-cooled and is equipped with a slot for droplet injection into the furnace. A movable-block swirl burner(12) with interchangeable fuel nozzles was mounted on the combustor and was capable of providing near-burner zone aerodynamic simulation of various flame types.(13)

The furnace, along with the near-burner module and modified front end, is shown in Figure 2-3. This unit was fired on natural gas at a nominal load of 90 kW. The excess air level was maintained at 30 percent ensuring that


R2
S3
S4
S1
R1
R3
S2
R4
Sampling Port at 34" From Front End
36" (91.4 cm)
Quartz Window (8" x 5")
3.625"(9.21 cm)
1.584"(4.02 cm)
0.625" (1.59 cm)
20.5" (52.1 cm)
30°
IFRF Burner
Water Passage

- Water-Cooled Shell
- 1 1/2" (3.81cm) Refractory Walls
- 8" x 5" (20.3 cm x 12.7 cm) Quartz Windows
- Quarl Exit/Furnace Diameter = 5.66
- S/R-Cooling Water Supply/Return

Design Criteria

- 310K BTU/Hr (90kW)
- 15% Excess Air
- Air Velocity at Throat = 85 FPS (25.9 m/s)
- Natural Gas Jet Velocity = 400 FPS (121.9 m/s)
- Combustor Wall Temperature = 1000°F (810K)
- Peak Flame Temperature = 2600°F (1700K)

Figure 2-1. Near burner module

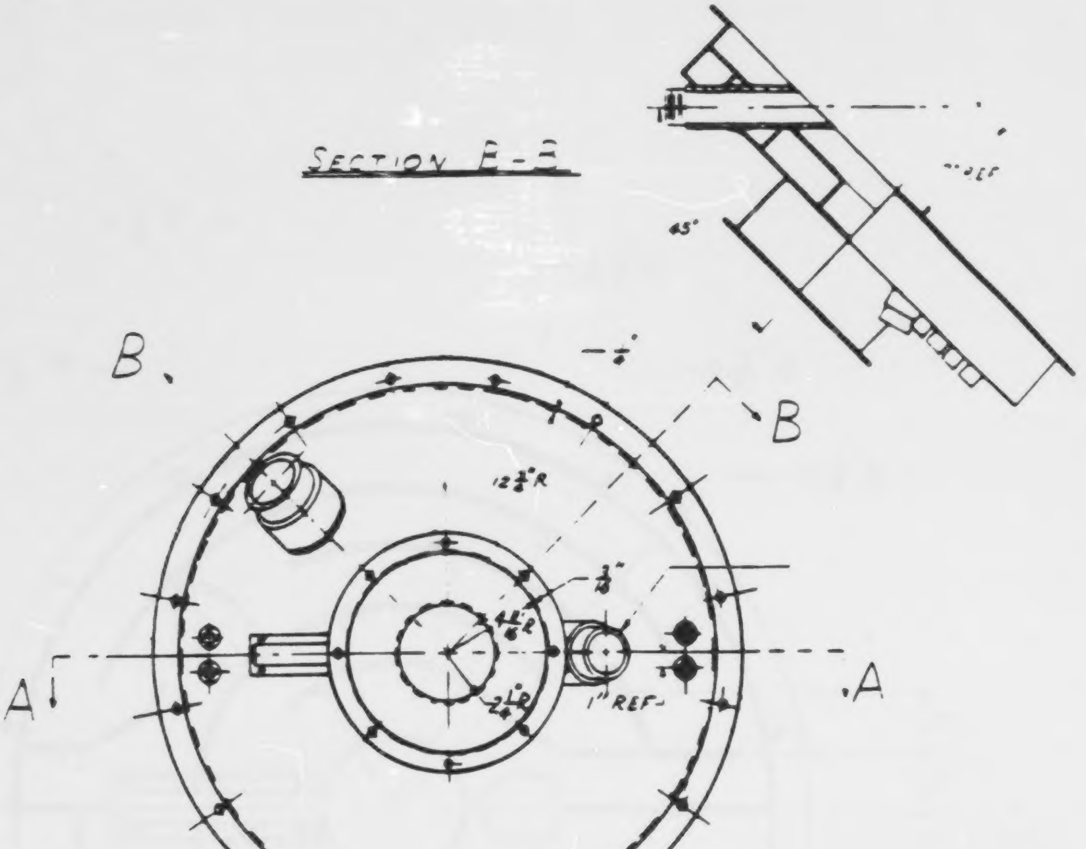
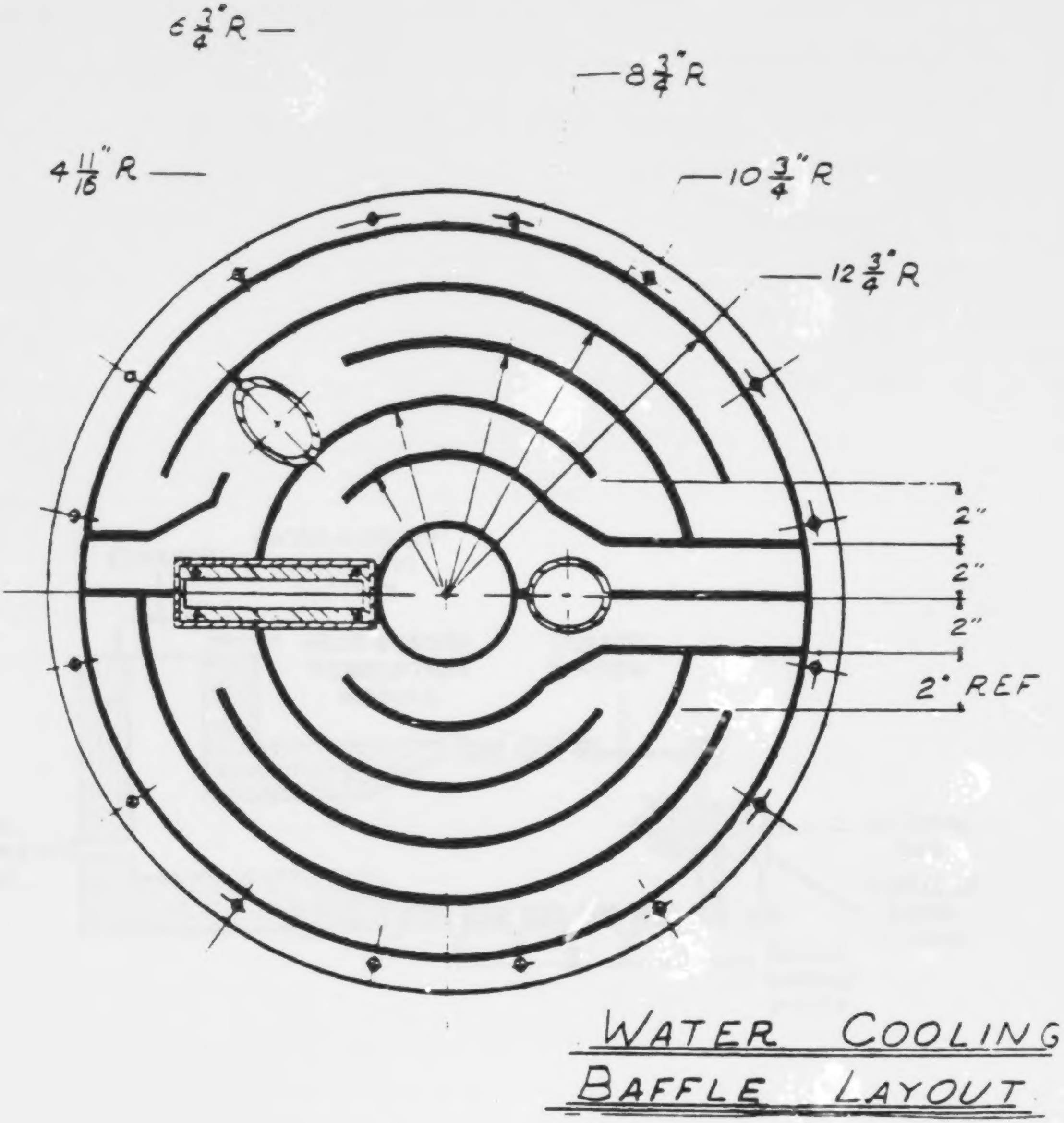

SECTION B-B
45°
B
B
12 3/8" R
3/16"
4 1/2" R
2 1/4" R
1" REF.
A
A
30°
1 1/2"
1/4"
5"
2"
2 1/2"
1/4"
6 1/2"
4"
1 1/2"
1/4"
7" REF.
SECTION A-A

Figure 2-2a. Rainbow combustor front end.



6 3/4" R
8 3/4" R
4 11/16" R
10 3/4" R
12 3/4" R
2"
2"
2"
2" REF
WATER COOLING
BAFFLE LAYOUT

Figure 2-2b. Rainbow combustor front end, water cooling baffle layout.

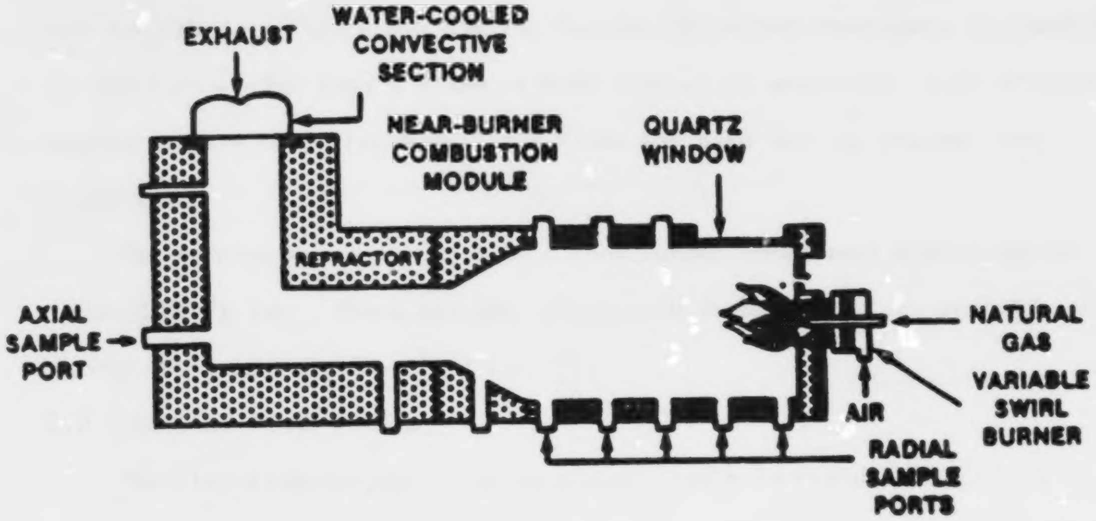

EXHAUST
WATER-COOLED CONVECTIVE SECTION
NEAR-BURNER COMBUSTION MODULE
QUARTZ WINDOW
REFRACTORY
AXIAL SAMPLE PORT
NATURAL GAS
VARIABLE SWIRL BURNER
AIR
RADIAL SAMPLE PORTS

Figure 2-3. Rainbow combustor

sufficient oxygen was available for droplet combustion. Natural gas flow was monitored by a Brooks rotameter calibrated for natural gas while the combustion air was supplied from a dedicated Worthington compressor and monitored by a venturi type flow element. The natural gas and combustion air measurement systems are described in Appendices A1 and A2, respectively.

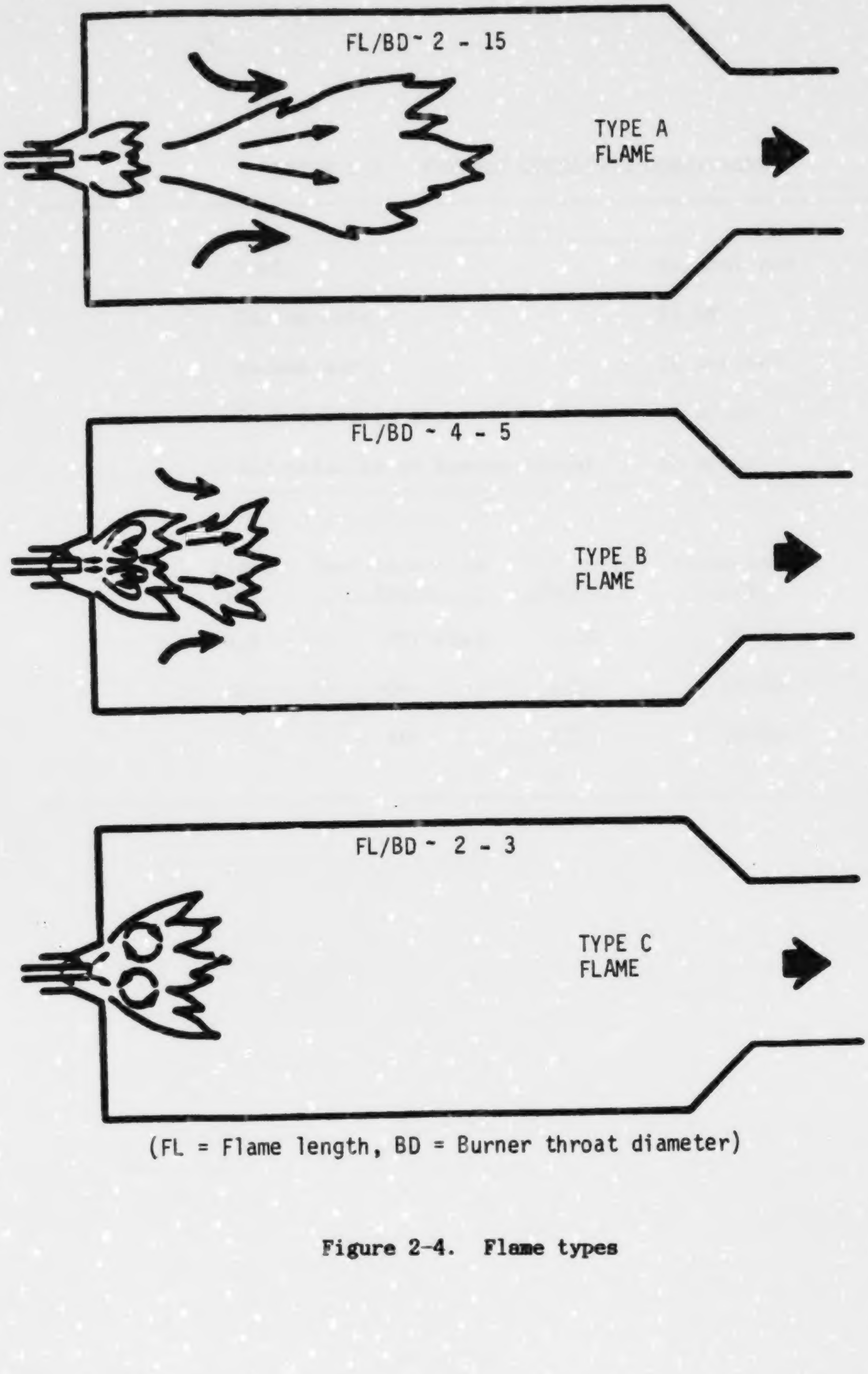
Two flame shapes with very different mixing patterns were established: Type C and Type A.(14) The Type C flame, produced with a high combustion air swirl (swirl number = 1.3, see Appendix A3) and a 45 degree fuel nozzle, was 10 to 15 cm long and was stabilized on the burner quarl by strong primary internal recirculation of the hot combustion gases. The Type A flame, produced with a minimum combustion air swirl for flame stabilization (swirl number = 0.6) and axial fuel injection, was 50 to 60 cm long. These flames are described in Figure 2.4 and the furnace operating conditions are described in Table 2-1. The Type C flame is most typical of practical, high efficiency combustion systems; therefore, this flame was used for the nominal test condition.

The furnace was equipped with a Coen Burner Management System and an induced draft fan. These systems, along with furnace startup, shutoff, and safety features, are described in (11).

## 2.2 THE FLAT-FLAME BURNER

The flat-flame burner is shown schematically in Figure 2-5. It is 18" x 12" x 3" in size and of stainless steel construction. Premixed air and fuel enter the combustion chamber through a sintered stainless steel plate. Transport of air/fuel mixture through the sintered stainless steel plate causes the velocity distribution of the mixture to be uniform, a necessary condition for achieving a flat flame. The sintered plate is water-cooled to prevent thermal distortion. The combustion chamber has large quartz windows for visual observations. Side ports on the burner (shown in Figure 2-5) allow

# FLAME TYPES


FL/BD ~ 2 - 15
TYPE A
FLAME
FL/BD ~ 4 - 5
TYPE B
FLAME
FL/BD ~ 2 - 3
TYPE C
FLAME

(FL = Flame length, BD = Burner throat diameter)

**Figure 2-4. Flame types**

## TABLE 2-1. FURNACE OPERATING CONDITIONS

Fuel - natural gas

Firing rate - 91 kW

Excess air - 30 percent

Fuel jet velocity - 45 m/sec

Air velocity at burner throat - 28 m/sec

| Flame Type | Fuel Injection Angle | Air Swirl Number | Flame Length (cm) |
|---|---|---|---|
| A/B | 0° (axial) | 0.65 | 50-60 |
| B | 0° | 1.3 | 15-18 |
| C | 45° | 1.3 | 10-13 |

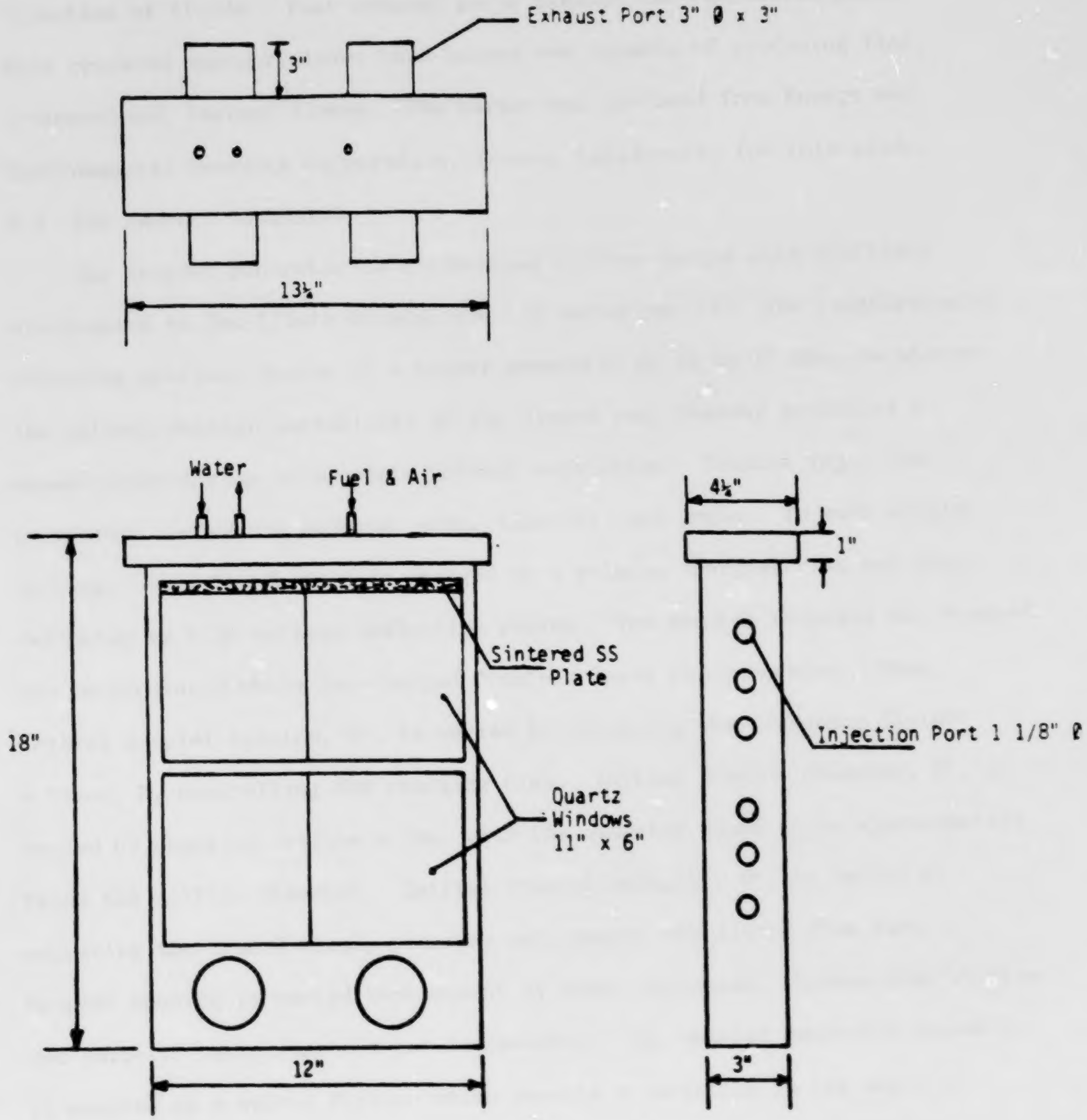

Exhaust Port 3" Ø x 3"
3"
13½"
Water
Fuel & Air
18"
Sintered SS Plate
Quartz Windows 11" x 6"
12"
4¼"
1"
Injection Port 1 1/8" Ø
3"

**Figure 2-5. Flat flame burner**

injection of fluids. Four exhaust ports exhaust the combustion gases. When operated appropriately, this burner was capable of producing flat, 2-dimensional laminar flames. The burner was borrowed from Energy and Environmental Research Corporation, Irvine, California, for this study.

## 2.3 THE DROPLET GENERATOR

The droplet generator is a vibrating orifice device with ancillary electronics to facilitate droplet spacing variation.(15) The longitudinally vibrating orifice, driven by a signal generator at 12 to 15 kHz, reinforces the natural Raleigh instability of the liquid jet, thereby producing a monodisperse stream of droplets without satellites. Droplet injection parameters varied are spacing, size, velocity, and angle. To vary droplet spacing, every Nth droplet is charged by a pulsing charging ring and then deflected by high voltage deflection plates. The neutral droplets are trapped and recirculated while the charged droplets leave the generator. Thus, initial droplet spacing, $L^{\circ}$, is varied by adjusting the frequency divider setting, N, controlling the charging ring. Initial droplet diameter, $D^{\circ}$, is varied by changing orifice sizes, with the diameter found to be approximately twice the orifice diameter. Initial droplet velocity, $V^{\circ}$, is varied by adjusting the liquid supply pressure and, hence, the liquid flow rate. Droplet spacing is varied independent of other variables, whereas droplet size and velocity variations are not independent. The droplet generator assembly is mounted on a swivel fixture which permits a variation in the angle of droplet injection. The droplet generator and the fixture are shown in Figures 2-6 and 2-7, respectively while the ancillary electronic circuit used to control droplet spacing is shown in Figure 2-8. The liquid feed system and the test liquid selection and properties are described in Appendices A4 and A5, respectively.

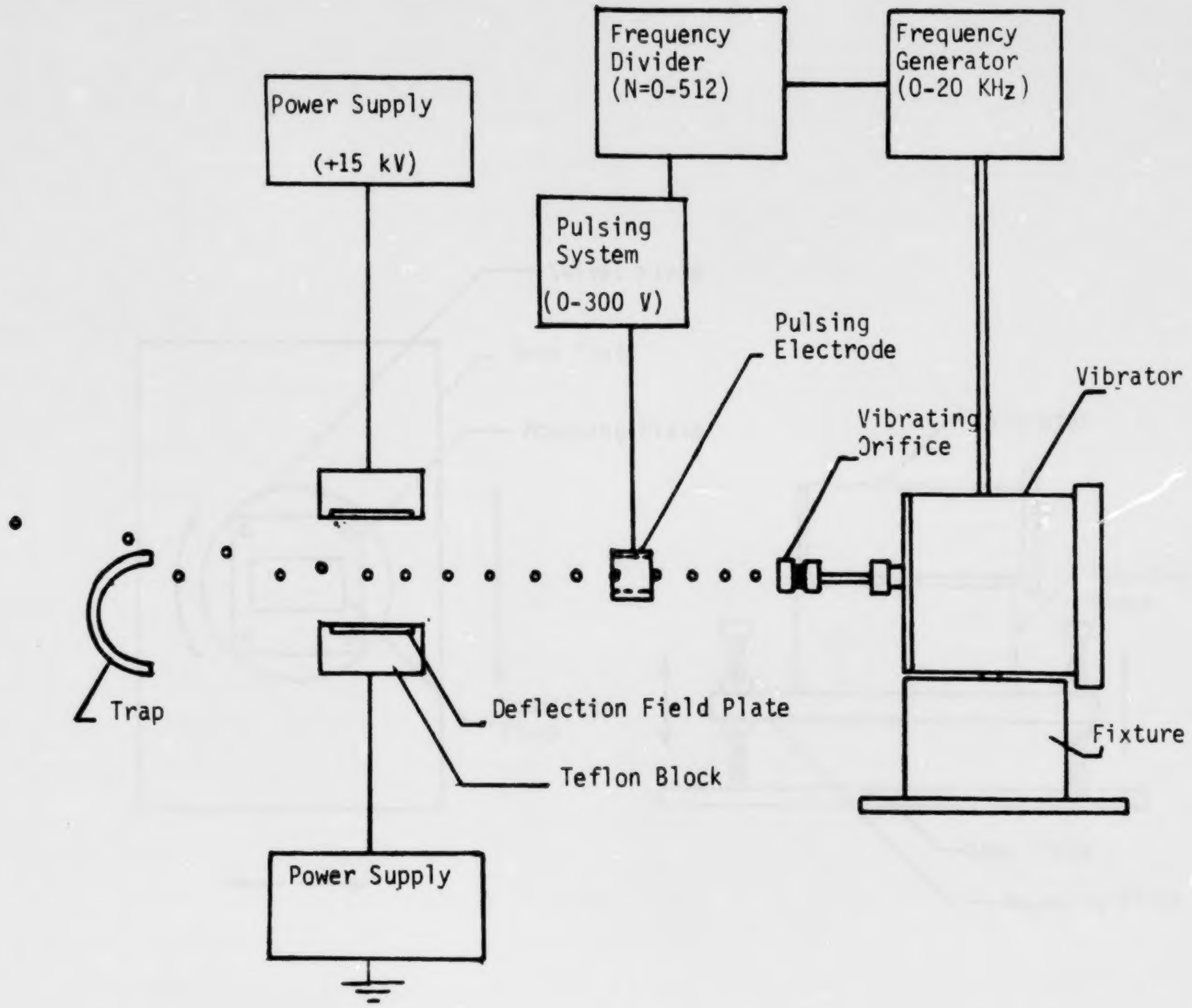

Power Supply
(+15 kV)
Frequency Divider (N=0-512)
Frequency Generator (0-20 KHz)
Pulsing System (0-300 V)
Pulsing Electrode
Vibrator
Vibrating Orifice
Trap
Deflection Field Plate
Teflon Block
Fixture
Power Supply

**Figure 2-6. Schematic of droplet generator**

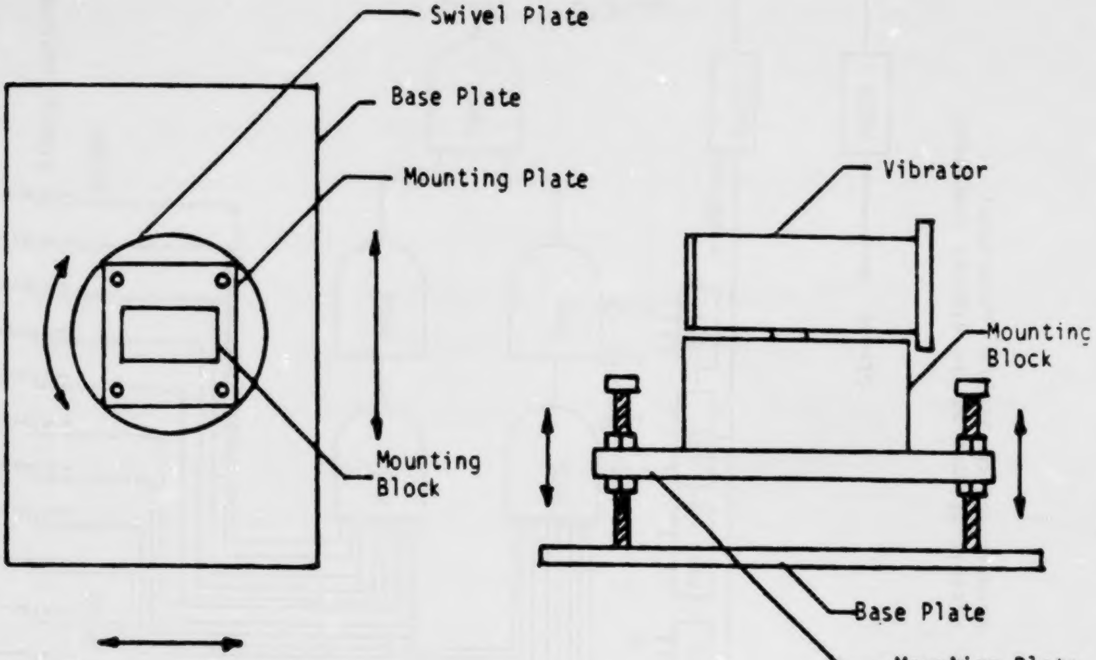

Swivel Plate
Base Plate
Mounting Plate
Mounting Block
Vibrator
Mounting Block
Base Plate
Mounting Plate

Figure 2-7. Schematic of the fixture and its range of motions

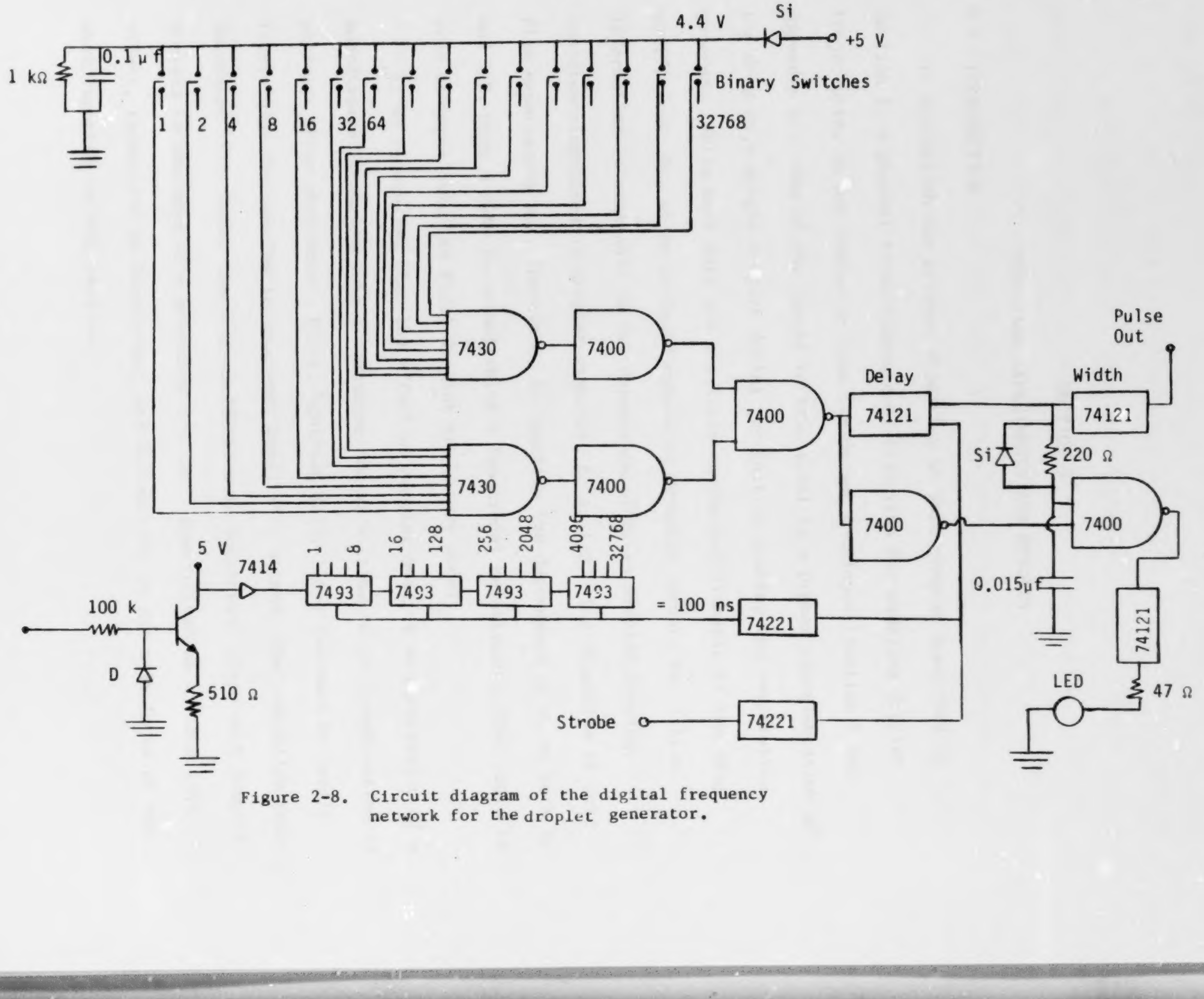

4.4 V
Si
+5 V
1 kΩ
0.1 μf
Binary Switches
1
2
4
8
16
32
64
32768
7430
7400
7430
7400
7400
Pulse
Out
Delay
74121
Width
74121
Si
220 Ω
7400
7400
0.015μf
74121
LED
47 Ω
5 V
7414
100 k
D
510 Ω
1
8
16
128
256
2048
4096
32768
7493
7493
7493
7493
= 100 ns
74221
Strobe
74221

Figure 2-8. Circuit diagram of the digital frequency network for the droplet generator.

# SECTION 3

## COLD FLOW EXPERIMENTS AND RESULTS

### 3.1 INTRODUCTION

To accomplish the primary objective of this program described in Section 1, a general three-dimensional algorithm for modeling droplet trajectories in hot combustor flow fields was developed (Section 5 and Appendix D). One of the inputs to this model is a proper representation of the drag on a single droplet during the initial heating and evaporation process. While much data are available on the relationship of the drag coefficient, $C_D$, of an isolated sphere to Reynolds number, Re, little information is available on the dependence of $C_D$ on droplet spacing, non-dimensionalized by droplet diameter, D, as L/D. The objective of cold flow experiments was, therefore, to quantify the dependence of $C_D$ on both $R_e$ and L/D, with a view to establishing a functional relationship that could be used as input into the final droplet trajectory model.

It is recognized that the effect of droplet spacing on penetration of a monodispersive stream into a combustor can be attributed to a combination of at least three phenomena. First, ignition delay times increase by nearly fourfold as the spacing is made very small(16); second, the combustion rate is decreased(17); third, the drag coefficient is decreased, since each droplet travels in the wake of a preceding droplet. Quantification of this last effect, recognized by Sangiovanni and Kesten,(16) is the sole focus of the work reported in this section.

## 3.2 THEORY

### Drag Coefficient

When droplets cease to interact, the drag coefficient, $C_D^\infty$, for each one is that of an isolated sphere. The conventional correlation for the drag on a sphere in steady motion is typically presented as a plot denoted as the "standard drag curve," where $C_D$ is plotted as a function of Re.(18) Many empirical or semi-empirical equations have been used to approximate this curve. For the slightly distorted droplets formed by a vibrating capillary droplet generator, the relation of Lambiris and Combs(19) has been recommended.(20)

$$\begin{aligned} C_D^\infty(Re) &= 27\ Re^{-0.84} \quad , 0 \le Re \le 80 \\ &= 0.27\ Re^{0.217} \quad , 80 \le Re \le 10^4 \\ &= 2 \quad , Re \ge 10^4 \end{aligned} \tag{3-1}$$

In the other extreme, as droplet spacing approaches the droplet diameter, the drag coefficient may be assumed to approach the friction drag coefficient of a long rod, $C_{ROD}$. For very long rods, the theory of Glauert and Lighthill(21) yields(22):

$$C_{ROD}(Re) = 0.755/Re \tag{3-2}$$

A general form for the asymptotic form for the drag coefficient, $C_D^0$ of a sphere as L/D approaches unity is obtained by a Taylor expansion about L/D = 1; thus, $C_D^0$ is hypothesized to be:

$$C_D^0(Re, L/D) = C_{ROD}(Re) + aRe^b\ \{L/D-1\} \tag{3-3}$$

where a and b are parameters to be determined from experiment. The factor $aRe^b$} multiplying {L/D-1} is hypothesized to be a function of Reynolds number, since the extent of droplet interaction as L/D approaches unity will depend on Re, the latter quantity determining the length of wake behind each droplet.(23)

Following Churchill(24) and Churchill and Usagi,(25) an effective and universal technique to correlate data, obtained between regions of validity for the asymptotic forms for $C_D$ as $L/D \to 1$ and $L/D \to \infty$, is to use the following expression for $C_D$, valid for all values of L/D:

$$\{C_D\ (Re, L/D)\}^{-n} = \{C_D^{o}\ (Re, L/D)\}^{-n} + \{C_D^{\infty}\ (Re)\}^{-n} \qquad (3\text{-}4)$$

where n is a parameter to be obtained by experiment. Equation (3-4), therefore, represents an expression for the drag coefficient, $C_D$, of a droplet, where the asymptotic limits $C_D^{o}$ and $C_D^{\infty}$ are given by Equations (3-1) and (3-3). The model contains three unknown parameters, a, b, and n; a and b determine the dependence on L/D as $L/D \to 1$, and the effect of Reynolds number on this dependence, while n determines how $C_D$ approaches its limiting value at $L/D \to \infty$.

The extent to which droplet spacing influences the local drag coefficient depends on the length of wake behind each droplet. Fornberg (26) calculated the wake length behind a cylinder for a range of Reynolds numbers up to 300. He found that wake length increases from Reynolds numbers 2 to 260. Above Re = 260, the wake region ceases to increase but becomes slightly shorter and wider. These results have relevance to this problem because, even though the drag coefficient of an isolated sphere is about half of that for an isolated cylinder, the dependence of $C_D$ on Re is similar. Therefore, it may be hypothesized that the dependence of wake length on Re is also similar. Hence, the linear dependence of wake length on Re suggests that the parameter b in Equation (3-3) should be approximately equal to -1.0.

In this work, the parameters a, b, and n are determined entirely from experimental data. However, for Re > 250, where the wake length may be considered to be roughly constant, only a few data points were collected, making it impossible to confirm that the limiting droplet separation, at which interactions cease to be important, is also independent of Re. Therefore, this hypothesis was assumed to be true, and a discontinuity in the model was introduced to ensure that, for Re > 250, the value of L/D, at which $C_D = 0.95\, C_D^{\infty}$, no longer depends on Re. Thus, the model for the effect of droplet spacing on the local drag coefficient is consistent with available calculations on the effect of Re on wake length behind a cylinder.

Trajectory Model

A simple force balance comprises the model to predict droplet trajectories in a quiescent environment:

$$\Sigma F_x = ma_x = -C_D \{\rho_a V^2 A/2\} \cos \theta \qquad (3\text{-}5)$$

$$\Sigma F_y = ma_y = C_D \{\rho_a V^2 A/2\} \sin \theta - mg \qquad (3\text{-}6)$$

These equations yield:

$$\frac{dx}{dt} = p \qquad (3\text{-}7)$$

$$\frac{dp}{dt} = -\frac{3\rho_a}{4\rho_d D} C_D p \{p^2 + q^2\}^{1/2} \qquad (3\text{-}8)$$

$$\frac{dy}{dt} = q \qquad (3\text{-}9)$$

$$\frac{dq}{dt} = -\frac{3\rho_a}{4\rho_d D} C_D q \{p^2 - q^2\}^{1/2} - g \qquad (3\text{-}10)$$

with

$$x(0) = 0,\ y(0) = 0,\ p(0) = V^o,\ q(0) = 0 \qquad (3\text{-}11)$$

Complexities arise in that $C_D$ (Equation 4) is a function of Re and L/D, both of which are continuously changing in the Lagrangian frame of reference. Conservation of mass yields:

$$L(t) = L^o V(t)/V^o \qquad (3\text{-}12)$$

where $V = \{p^2 + q^2\}^{1/2}$. Thus, instantaneous values of droplet spacing and, subsequently, instantaneous values of $C_D$ (Re, L/D) can be computed. For given values of a,b, and n, Equations (3-7) through (3-10) were numerically integrated to yield x(t), y(t), and y(x), using Equations (3-1), (3-3), (3-4), and (3-12) to evaluate $C_D$.

## 3.3 EXPERIMENTAL METHODS

### Apparatus

The droplet generator described in Section 2.3 was used to generate monodisperse droplets. The neutral droplets were trapped and recirculated while the charged droplets entered a trajectory observation tunnel where fluctuating air currents are minimized (Figure 3-1).

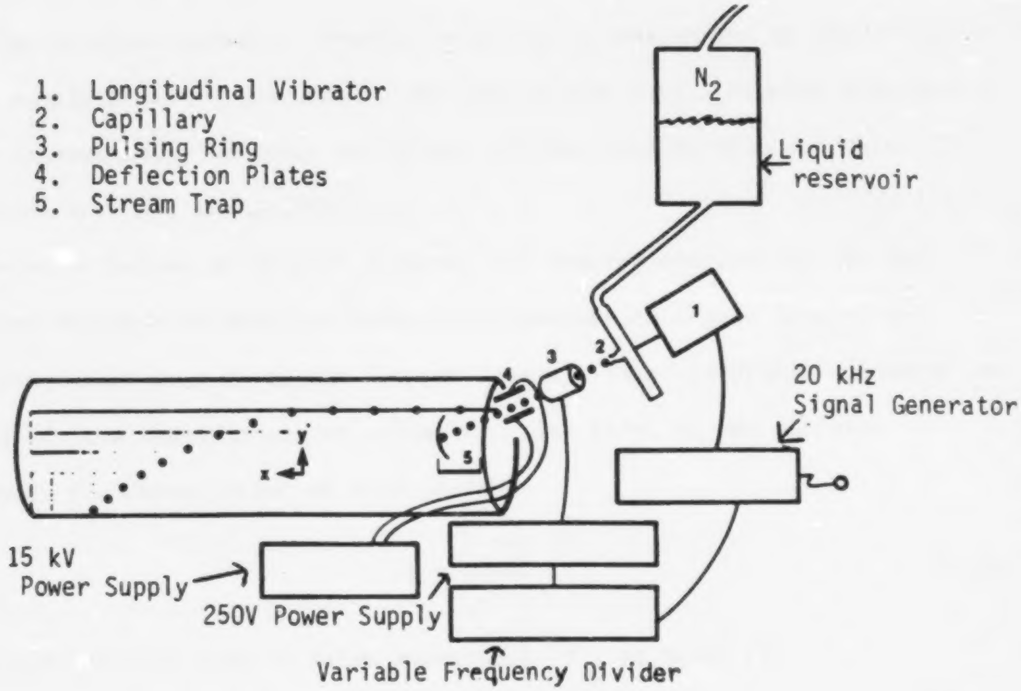

1. Longitudinal Vibrator
2. Capillary
3. Pulsing Ring
4. Deflection Plates
5. Stream Trap
$N_2$
Liquid reservoir
1
2
3
4
5
y
x
20 kHz Signal Generator
15 kV Power Supply
250V Power Supply
Variable Frequency Divider

Figure 3-1. Monodisperse droplet generator with ancillary electronics and two-dimensional trajectory measurement apparatus

Two fluids, chosen on the basis of conductivity (for electrostatic charging and deflection) and viscosity (for droplet formation), were tested. The first, a mixture of 80 percent (by volume) Shell Oil Company fuel additive ASA-3, comprised mostly of xylene ($C_8H_{10}$), and 20 percent (by volume) distillate fuel oil, was used for its applicability to combustion fuel atomization studies; the second, a mixture of water ($H_2O$) and glycerine ($C_3H_8O_3$), was used for comparison. Liquid feed system is described in Appendix A4 and test liquid selection and properties are given Appendix A5. Droplet parameters varied were spacing, size, and velocity. Spacing, non-dimensionalized as L/D, was varied by adjusting the frequency divider setting, N, which controls the charging ring pulse rate. Size, D, was varied by changing orifice sizes, with droplet diameters found to be approximately twice the orifice diameter. Droplet velocity, V, was varied by adjusting the liquid supply pressure and, hence, the liquid flow rate. Droplet spacing was varied independently of other variables, whereas droplet size and velocity variations were not independent.

Relative values of droplet diameter and droplet spacing, $L_s$, in the uncharged stream were measured using a strobescope to freeze droplet motion and a microscope to magnify the droplet images. Absolute droplet diameter was calculated from measurements of volumetric flow rate, $\dot{q}$, and vibrator frequency, f. Conservation of mass yields:

$$D = \left[\frac{6\dot{q}}{\pi f}\right]^{1/3} \tag{3-13}$$

The initial droplet spacing after separation, $L^o$, is given by:

$$L^o = L_s N \tag{3-14}$$

Initial droplet velocity, $V^o$, is given by:

$$V^o = L_s f \tag{3-15}$$

Measurement of droplet trajectories was performed by manually recording two-dimensional coordinates from droplet shadows on graph paper. The trajectory starting point was defined at the center of the deflection plates, where the droplet path was horizontal as determined by a level gauge.

Approach

Experimental measurements consisted of full trajectories and trajectory endpoints. Full trajectories contained between a minimum of six and a maximum of fifteen x-y coordinate pairs describing the complete trajectory of a droplet from the injection point to an endpoint that lay between 11.7 and 14.8 cm below. Trajectory endpoints, on the other hand, consisted merely of the horizontal distance travelled for a given vertical height, ranging from 7 to 14 cm.

Parameter estimation was accomplished by non-linear regression of data for ten full trajectories (#1 through #10 on Table 3-1). Initial Reynolds number was 210 and initial droplet spacing to diameter ratio was varied form 2.7 to 1365 ($1 \leq N \leq 512$). It should be noted, however, that local values of both Re and L/D changed dramatically during the course of each single trajectory, thus allowing a Re dependence to be determined.

Four additional full trajectories (#11 through #14) yielded data at higher initial Reynolds numbers. These were compared to model predictions. Thirty-nine trajectory endpoints, spanning a wider range of parameters ($90 < Re^o < 292$, $6.7 < V^o < 9.9$ m/s, $205 < D < 450$ $\mu$m, $2.4 < L^o/D < 1500$), completed the comparison between prediction and experiment.

## 3.4 EXPERIMENTAL RESULTS

Data from full trajectory and trajectory endpoint measurements are presented in Tables 3-1 and 3-2, respectively. Accuracy of trajectory coordinates was estimated to be ±0.2 cm. In addition, some data scatter was

## TABLE 3-1
## FULL TRAJECTORY DATA

| Trajectory[1] | X(cm) | Y(cm) |
|---|---|---|
| #1 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.13 |
| Re*=211 | 28.8 | -0.25 |
| L*/D=2.67 | 39.0 | -0.38 |
| | 54.2 | -0.89 |
| | 69.5 | -2.03 |
| | 84.7 | -3.81 |
| | 99.9 | -6.35 |
| | 122.8 | -11.7 |
| #2 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.25 |
| Re*=211 | 28.8 | -0.38 |
| L*/D=5.33 | 39.0 | -0.64 |
| | 54.2 | -1.52 |
| | 69.5 | -2.79 |
| | 84.7 | -6.60 |
| | 105.0 | -11.7 |
| #3 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.25 |
| Re*=211 | 28.8 | -0.38 |
| L*/D=10.7 | 39.0 | -0.64 |
| | 54.2 | -1.78 |
| | 69.5 | -4.06 |
| | 87.2 | -11.7 |
| #4 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.25 |
| Re*=211 | 28.8 | -0.51 |
| L*/D=21.3 | 39.0 | -0.76 |
| | 54.2 | -2.29 |
| | 69.5 | -4.57 |
| | 84.7 | -11.7 |
| #5 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.25 |
| Re*=211 | 28.8 | -0.64 |
| L*/D=42.6 | 39.0 | -0.89 |
| | 54.2 | -2.29 |
| | 69.5 | -5.84 |
| | 82.2 | -11.7 |
| #6 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.51 |
| Re*=211 | 28.8 | -0.76 |
| L*/D=85.3 | 39.0 | -1.27 |
| | 54.2 | -2.54 |
| | 77.1 | -11.7 |
| #7 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.51 |
| Re*=211 | 28.8 | -0.76 |
| L*/D=171 | 39.0 | -1.52 |
| | 54.2 | -4.06 |
| | 72.2 | -11.7 |
| #8 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.51 |
| Re*=211 | 28.8 | -0.76 |
| L*/D=341 | 39.0 | -2.03 |
| | 54.2 | -4.57 |
| | 68.2 | -11.7 |
| #9 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.51 |
| Re*=211 | 28.8 | -0.76 |
| L*/D=682 | 39.0 | -1.52 |
| | 68.2 | -11.7 |
| #10 | 5.0 | 0.0 |
| D=324 μm | 8.5 | -0.13 |
| V*=10.02 m/s | 18.7 | -0.51 |
| Re*=211 | 28.8 | -1.02 |
| L*/D=1365 | 39.0 | -1.78 |
| | 69.5 | -11.7 |
| #11 | 5.0 | 0.0 |
| D=234 μm | 7.5 | -0.05 |
| V*=7.72 m/s | 17.5 | -0.29 |
| Re*=117 | 28.0 | -0.54 |
| L*/D=2.54 | 38.0 | -1.3 |
| | 48.0 | -2.1 |
| | 58.0 | -2.8 |
| | 69.0 | -4.5 |
| | 79.0 | -6.7 |
| | 89.0 | -7.9 |
| | 99.0 | -11.0 |
| | 109.0 | -13.5 |
| | 104.0 | -14.8 |
| #12 | 5.0 | 0.0 |
| D=234 μm | 13.0 | -0.16 |
| V*=7.72 m/s | 18.0 | -0.32 |
| Re*=117 | 28.0 | -0.95 |
| L*/D=162 | 39.0 | -2.9 |
| | 49.0 | -7.9 |
| | 55.0 | -13.0 |
| #13 | 5.0 | 0.0 |
| D=450 μm | 7.5 | -0.05 |
| V*=9.95 m/s | 17.5 | -0.29 |
| Re*=292 | 28.0 | -0.54 |
| L*/D=1.70 | 38.0 | -1.05 |
| | 48.0 | -1.3 |
| | 58.0 | -2.06 |
| | 69.0 | -2.09 |
| | 79.0 | -3.19 |
| | 89.0 | -4.86 |
| | 99.0 | -6.2 |
| | 109.0 | -7.65 |
| | 119.0 | -9.7 |
| | 129.0 | -12.0 |
| | 135.0 | -14.8 |
| #14 | 5.0 | 0.0 |
| D=450 μm | 9.0 | -0.3 |
| V*=9.95 m/s | 19.0 | -0.5 |
| Re*=292 | 29.0 | -0.6 |
| L*/D=109 | 39.0 | -1.3 |
| | 49.0 | -2.3 |
| | 60.0 | -3.6 |
| | 70.0 | -5.8 |
| | 95.0 | -14.0 |

[1] Trajectories 1 through 10 with 80% $C_8H_{10}$/20% No. 2 fuel oil droplet; trajectories 11 through 14 with 75% $H_2O$/25% $C_3H_8O_3$ droplet.

## TABLE 3-2.
## SINGLE POINT TRAJECTORY DATA

| Fluid[1] | D (μm) | $V^*$ (m/s) | $Re^*$ | $L^*/D$ | Height (cm) | Range (cm) |
|---|---|---|---|---|---|---|
| 1 | 205 | 6.71 | 89.6 | 2.52 | 8.89 | 61 |
| | | | | 5.04 | 8.57 | 51 |
| | | | | 10.1 | | 43 |
| | | | | 20.2 | | 37 |
| | | | | 40.3 | | 33 |
| | | | | 80.7 | | 32 |
| | | | | 161 | | 28 |
| | | | | 323 | | 28 |
| | | | | 646 | | 27 |
| | | | | 1291 | | 27 |
| 2 | 225 | 7.02 | 110 | 2.40 | 7.30 | 76 |
| | | | | 4.80 | | 71 |
| | | | | 9.60 | | 63 |
| | | | | 19.2 | | 56 |
| | | | | 38.4 | | 53 |
| | | | | 76.8 | | 50 |
| | | | | 154 | | 48 |
| | | | | 307 | | 48 |
| | | | | 614 | | 48 |
| | | | | 1229 | | 47 |
| 2 | 234 | 8.89 | 136 | 2.92 | 7.30 | 86 |
| | | | | 5.85 | | 84 |
| | | | | 11.7 | | 76 |
| | | | | 23.4 | | 66 |
| | | | | 46.8 | | 61.5 |
| | | | | 93.5 | | 61 |
| | | | | 187 | | 54.5 |
| | | | | 374 | | 54.5 |
| | | | | 748 | | 54.5 |
| | | | | 1497 | | 54.5 |
| 3 | 450 | 9.94 | 292 | 3.40 | 13.97 | 118 |
| | | | | 6.80 | | 115 |
| | | | | 13.6 | | 110 |
| | | | | 27.2 | | 103 |
| | | | | 54.4 | | 100 |
| | | | | 109 | | 95 |
| | | | | 218 | | 94 |
| | | | | 435 | | 91 |
| | | | | 870 | | 91 |

[1] Fluid 1: 80% $C_8H_{10}$/20% No. 2 fuel oil
Fluid 2: 50% $H_2O$/50% $C_3H_8O_3$
Fluid 3: 75% $H_2O$/25% $C_3H_8O_3$

observed, approximating a ±2 cm variation in the horizontal position at the trajectory endpoint.

## Parameter Estimation

Parameters a, b, and n were estimated using data from the first 10 trajectories of Table 3-1. Non-linear regression for parameter estimation was achieved using a modified Marquardt(27) algorithm, based on a multi-dimensional search in parameter space for the minimum value of a sum of squares function measuring deviation from the data. A special feature of the algorithm used is that it calculates the sensitivity matrix $\{\partial F_i/\partial \theta_j\}$ relating the change in the i'th predicted value, $F_i$, with each parameter $\theta_j$. This quantity indicates which parameters contribute first order and second order effects. For example, sensitivity analysis indicated that a is the least sensitive parameter in the drag coefficient formulation, and, hence, one would expect rather wide confidence limits on this parameter.

The least squares parameter is estimated, obtained with all three parameters placed in regression, and approximate 95 percent confidence limit with parameter b held constant, are:

$a = 34.80 \pm 11.41$
$b = -1.009$
$n = 0.7072 \pm 0.086$

Parameters a and b, which determine the initial slope of $C_D$ as L/D-->1, are highly cross-correlated (correlation coefficient = -0.9994). Ordinarily this high correlation would be a problem, requiring one of the parameters to be fixed. However, with all three parameters in regression, the minimum sum of squares was achieved with b predicted to be almost exactly as hypothesized from Fornberg's analytical solution.(26) Therefore, the values shown above were used, although in estimating the 95 percent confidence limits parameter b was held constant at the previously determined value of -1.009. The confidence limits on parameter a reflect, therefore, the confidence limits on the initial slope of $C_D$ as L/D--->1, while those on parameter n reflect the confidence limits on the curvature of $C_D$ as $C_D \rightarrow C_D^{\infty}$. Furthermore, sensitivity analysis indicates very low sensitivity of the $C_D$ parameters during the initial portion of a droplet trajectory. The parameters are most sensitive at the trajectory endpoints. Therefore, prediction of trajectory endpoints comprises a severe test of the $C_D$ formulation and trajectory model.

Other statistical quantities that measured model adequacy were determined as follows:

$R^2$ = 0.989 (model effectiveness)

F-test = 0.04 (percent probability that model is not an improvement over no model at all)

Predictions

Model predictions are compared to experimental measurements in Figure 3-2 (full trajectories) and Figure 3-3 (trajectory endpoints). The upper portion of Figure 3-2 shows the model fit to 5 of the 10 trajectories used in the regression analysis. The experimental data shown cover the entire range of trajectories for various droplet spacings. The dashed line corresponds to the hypothetical limit of zero drag while, at the other extreme, the solid line for $L^o/D$ = 1365 represents the limit for isolated spheres. Droplet interactions lead to trajectories lying between these extremes and, clearly, are of first order importance. The remaining four trajectories (Figure 3-2 lower portion) are predicted reasonably well. The largest discrepancy arises at high initial Reynolds number ($Re^o$ = 292) and close initial spacing ($L^o/D$ = 1.70), when droplets penetrated almost to the end of the observation tube where the quiescent environment may have been disturbed.

The upper portion of Figure 3-3, depicting measured and predicted trajectory endpoints for all 10 trajectories included in regression, clearly shows the importance of droplet spacing in determining droplet penetration at

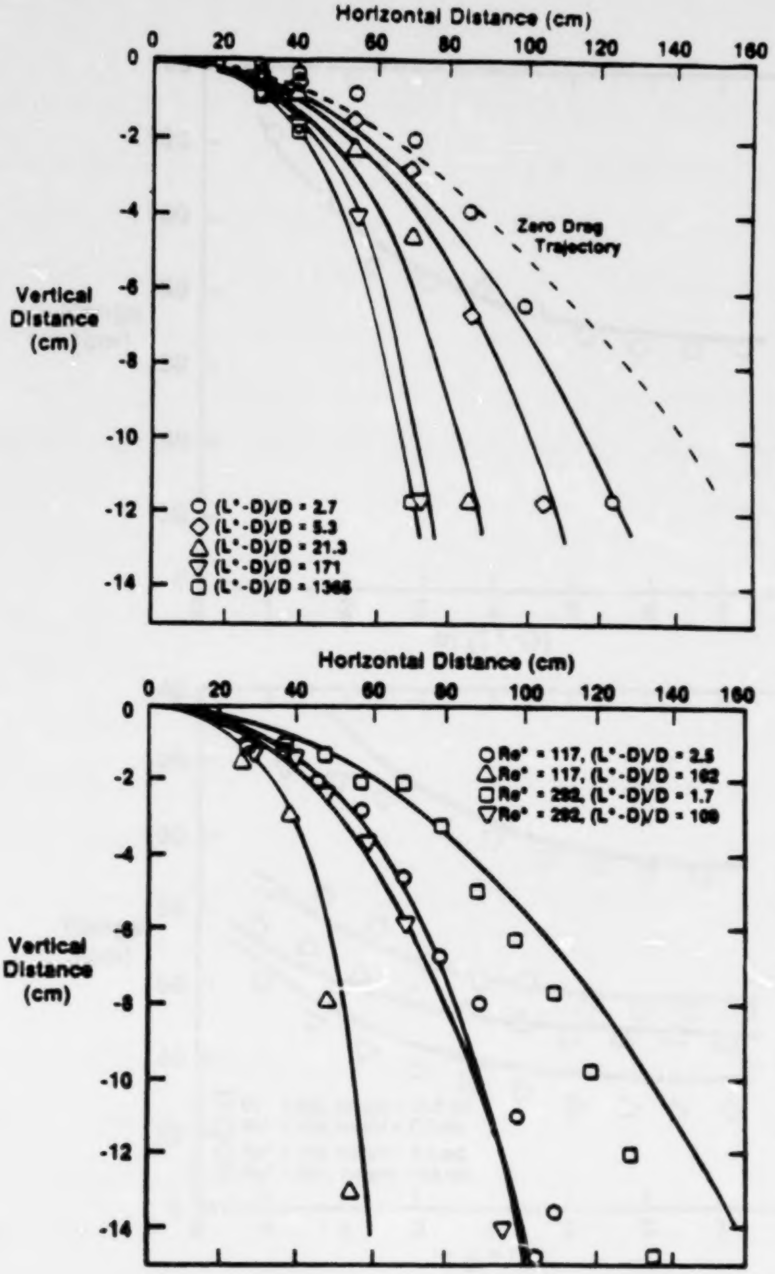


Figure 3-2. Two-dimensional droplet trajectories. Points represent measured trajectories; lines are model results.

Top plot: Results from the best-fit nonlinear regression of 10 full trajectories at Re* = 210. Shown are 5 trajectories.

○ (L*-D)/D = 2.7
◇ (L*-D)/D = 5.3
△ (L*-D)/D = 21.3
▽ (L*-D)/D = 171
□ (L*-D)/D = 1365

Bottom plot: Model predictions of 4 more fall trajectories.

○ Re* = 117, (L*-D)/D = (L*-D)/D = 2.5
△ Re* = 117, (L*-D)/D = 162
□ Re* = 292, (L*-D)/D = 1.7
▽ Re* = 292, (L*-D)/D = 109

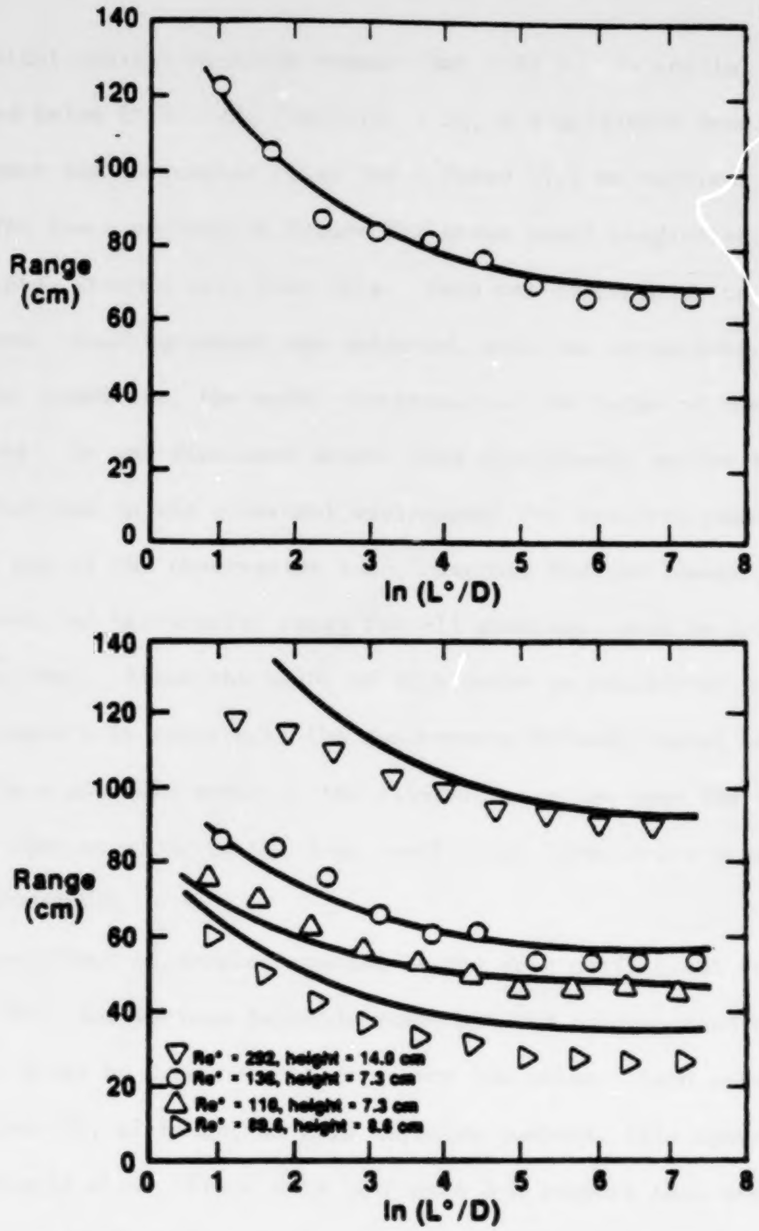


Figure 3-3. Droplet trajectory endpoints. Points represent measured trajectory endpoints; lines are model results.

Top plot: Results from the best-fit nonlinear regression of 10 full trajectories at Re* = 210, with the endpoint being the horizontal distance (range) that a droplet travels while falling a vertical distance (height) of 11.7 cm.

Bottom plot: Model predictions of 39 more trajectory endpoints.

▽ Re* = 292, height = 14.0 cm
○ Re* = 136, height = 7.3 cm
△ Re* = 110, height = 7.3 cm
▷ Re* = 89.6, height = 8.6 cm

a constant initial Reynolds number ($Re^o = 211$). As initial droplet spacing is reduced below $L^o/D = 150$ ($\ln(L^o/D) = 5$), a significant drag reduction greatly increases the horizontal range for a fixed 11.7 cm vertical drop.

The lower portion of Figure 3-3 shows model predictions for 39 trajectory endpoints, grouped into four sets. Each set corresponds to a different $Re^o$, as shown. Good agreement was achieved, with two exceptions. First, for the high $Re^o$ condition, the model overpredicted the range of the closely-spaced droplets. As was discussed above, this discrepancy may be due to perturbations in the quiescent environment for droplets penetrating too close to the end of the observation tube. Second, for the lowest $Re^o$, the model overpredicted the droplet range for all spacings, even as $L/D \to \infty$, where $C_D = C_D^\infty(Re)$. Since the shape of this curve is consistent with the data, but the asymptote is incorrect, the discrepancy between theory and experiment reflects a possible error in the literature values used for $C_D^\infty(Re)$ at low Re, rather than an error in the drag coefficient formulation presented here.

## 3.5 DISCUSSION

The effect of droplet spacing on the drag coefficient is shown in Figure 3-4, for various Reynolds numbers. The intersection of the vertical axis is given by $C_{ROD}$, which has a very low value. Each curve asymptotically approaches $C_D^\infty$, although, at high Reynolds numbers, this approach appears to be surprisingly slow. Since data in Figure 3-3 suggest that spacing has little practical effect on penetration when $L^o/D > 150$, it might be argued that the very slow final approach to the $C_D^\infty$ asymptote is an artifact of our formulation (Equation 3-4), and that it leads to negligible error in practice. For $L/D < 150$, however, it is clear that droplet spacing has a first order effect on the drag coefficient, which can be significantly diminished through aerodynamic interactions with the droplet neighbors.

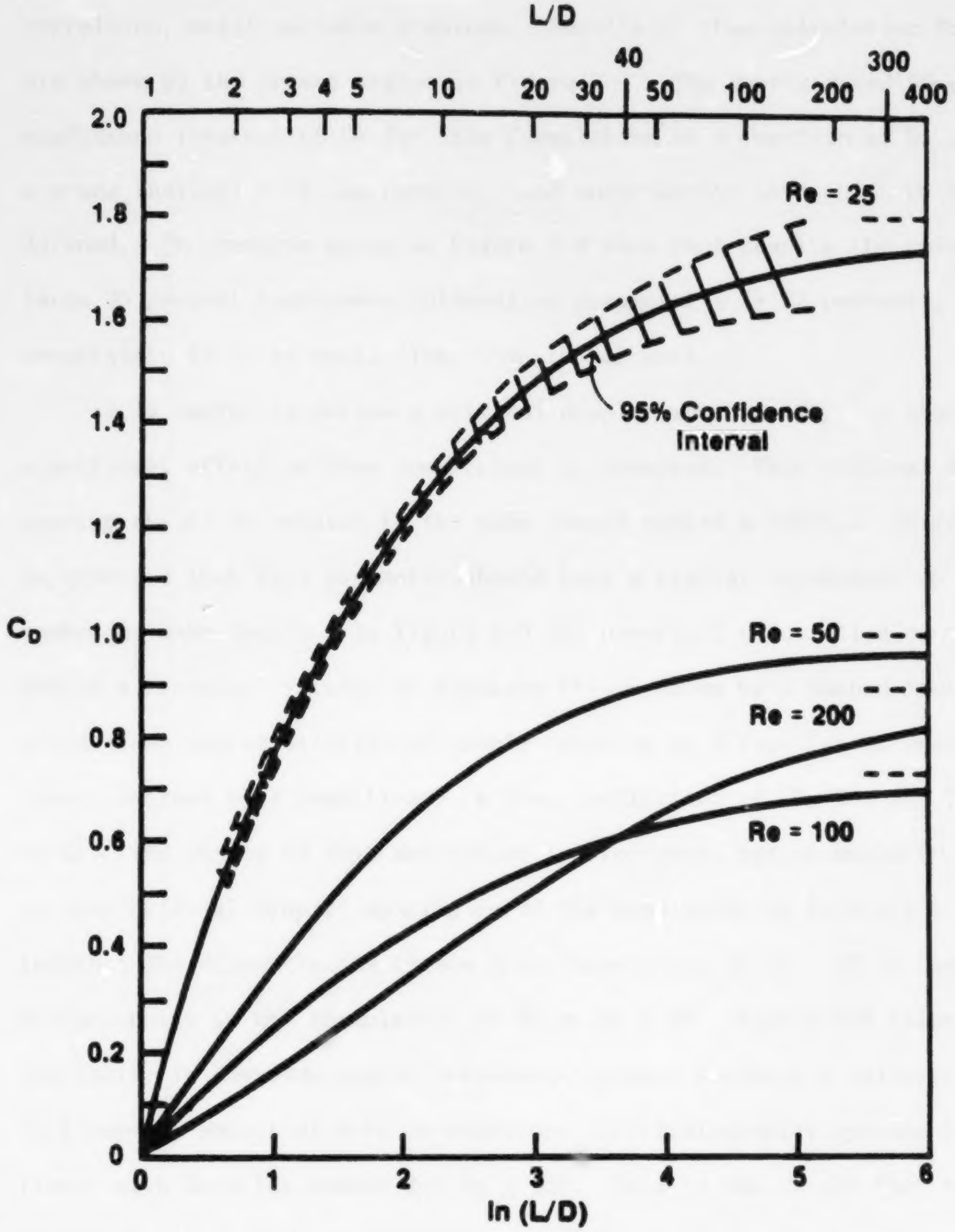


**Figure 3-4.** Droplet drag coefficient as a function of Re and L/D. The dotted lines on the right axis indicate the value of the drag coefficient of an isolated sphere at each Re value plotted.

The confidence limits on the individual drag coefficient parameters can be propagated to yield confidence limits on $C_D$ using a procedure for correlated, multi-variable problems. Results of this calculation for Re = 25 are shown by the shaded region in Figure 3-4. The approximated 95 percent confidence interval on $C_D$ for this formulation as a function of Re and L/D is a crude indication of the accuracy (and uncertainty) with which $C_D$ has been defined. The results shown in Figure 3-4 show that despite the relatively large 95 percent confidence interval on parameter a (± 33 percent), the uncertainty in $C_D$ is small (less than 10 percent).

It is useful to define a critical droplet spacing, $\{L/D\}_c$, above which no significant effect on drag coefficient is observed. This critical droplet spacing should be related to the wake length behind a sphere. Therefore, it is expected that this parameter should have a similar dependence on Reynolds number as wake length. In Figure 3-5 the numerical calculation of wake length behind a circular cylinder by Fornberg(26) is shown by a dashed line. The solid lines represent critical droplet spacing as a function of Reynolds number defined by 3 conditions: a drag coefficient of 65, 70, and 75 percent of $C_D^{\infty}$. The choice of this definition is arbitrary, but it would be convenient to have critical droplet spacing be of the same order as Fornberg's wake length. The discontinuity in the drag formulation at Re = 80 is due to a discontinuity in the formulation of $C_D^{\infty}$ at Re = 80. Figure 3-5 illustrates the similarity in Reynolds number dependence between Fornberg's calculations and this paper's empirical drag formulation. Critical droplet spacing is nearly linear with Reynolds number for Re $\leq$ 250. This is due to the fact that the estimated value for b is very close to -1.0.

It should be pointed out that even though the three parameter formulation of $C_D$, as a function of Re and L/D, predicted two-dimensional trajectories very well (provided $Re^o$ < 250) over the entire range of droplet spacings, it

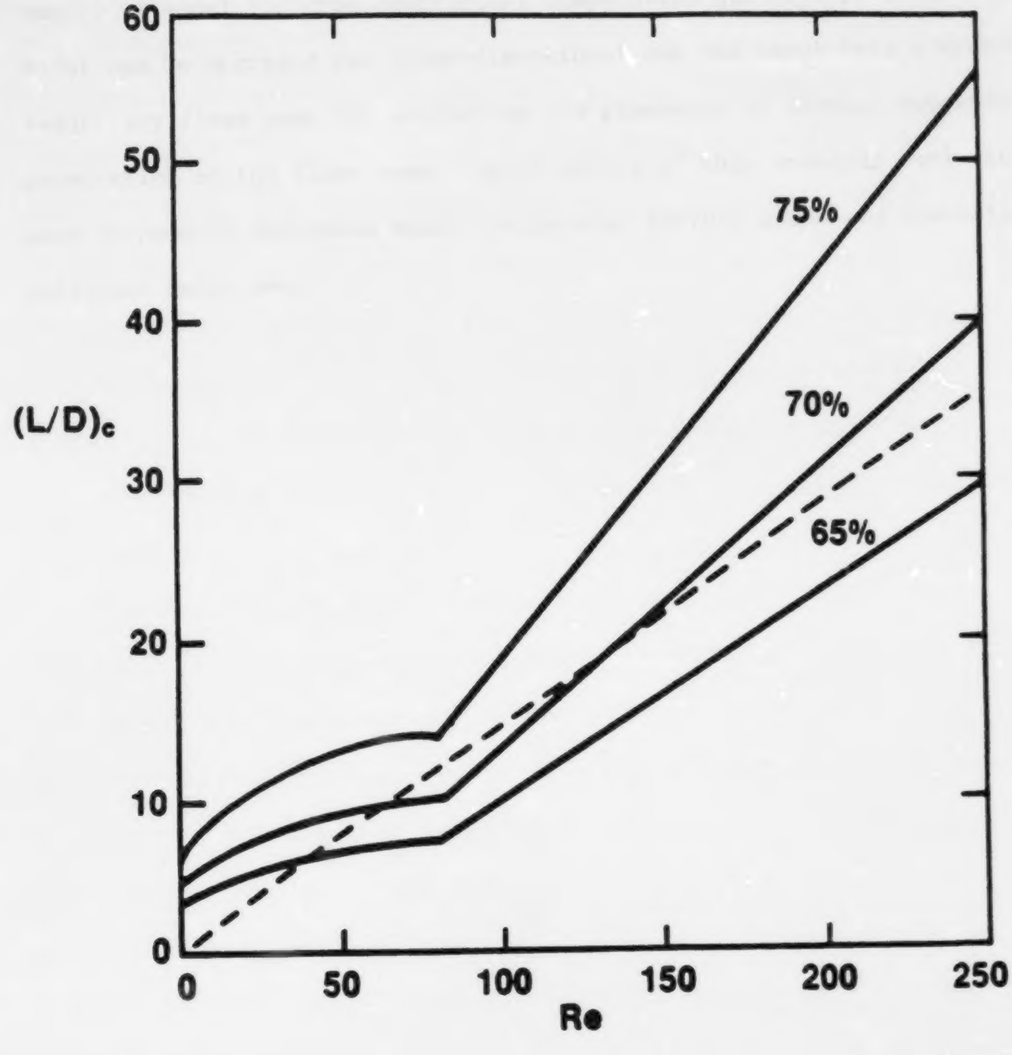


Figure 3-5. Critical droplet spacing as a function of Re for values of $C_D$ of 65, 70, and 75 percent of that of an isolated sphere. The dotted line represents the numerical solution of Forberg(28) for the wake length behind a circular cylinder.

may not be the only formulation that is valid. Other models may work as well, and indeed, it would be desirable to replace the empiricism in this report with a more mechanistic approach, such as, for example, that of Fornberg.(26)

In conclusion, the drag coefficient of a monodisperse stream has been found to be a function of both Reynolds number and droplet spacing. An empirical model for drag coefficient computation has been proposed. This model can be upgraded for three-dimensional use and input into a droplet trajectory flame code for evaluating the phenomena of droplet bypassing and penetration of the flame zone. Applications of this modeling tool can be used to predict hazardous waste incinerator failure modes and combustion pollutant emissions.

# SECTION 4

# TWO-DIMENSIONAL LAMINAR FLAME EXPERIMENTS AND RESULTS

## 4.1 INTRODUCTION

It is well known that interactions between droplets in spray combustion reduce droplet evaporation rates as compared with the case of the isolated droplet.(28-30) The smaller the interdroplet spacing in a spray, the stronger is the competition for available oxidizer. This droplet interaction was studied at EPA in a two-dimensional flat-flame burner system where turbulent effects were eliminated. Combustible and non-burning droplets were studied to differentiate droplet drag effects from droplet burning effects.

## 4.2 EXPERIMENTAL METHODS

### Apparatus

The flat-flame burner and the droplet generator (described in Section 2.2) along with other experimental hardware used for this series of experiments are shown in Figure 4-1. The burner was fired at 10-11 kBtu/hr on methane and air. A mixing chamber containing 3 mm glass beads was incorporated into the fuel and oxidizer line to prevent any flow pulsations from reaching the burner and to allow the fuel and air to mix properly. Fuel and air flows were controlled by two metering valves and measured by in-line rotameters. The combustion gases were exhausted into an air-hood.

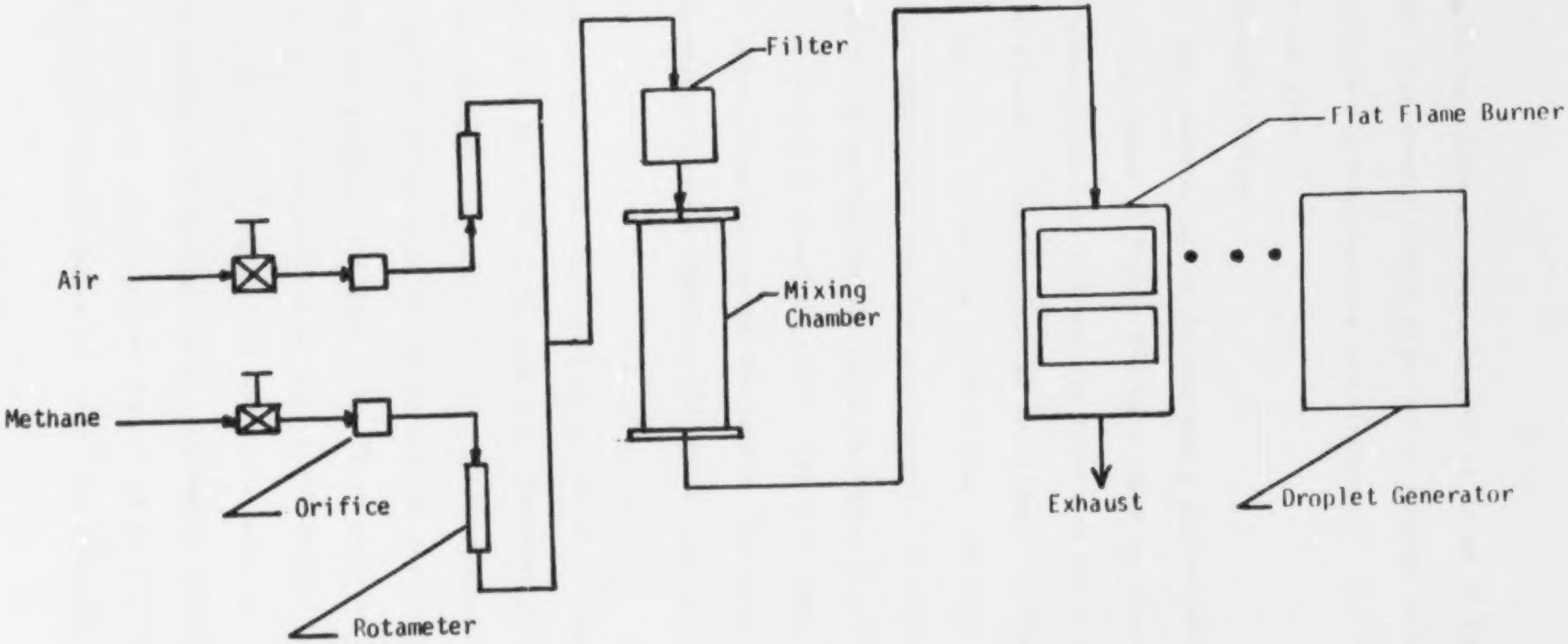

Filter
Flat Flame Burner
Air
Mixing
Chamber
Methane
Orifice
Exhaust
Droplet Generator
Rotameter

**Figure 4-1. A schematic of the flat-flame burner set-up**

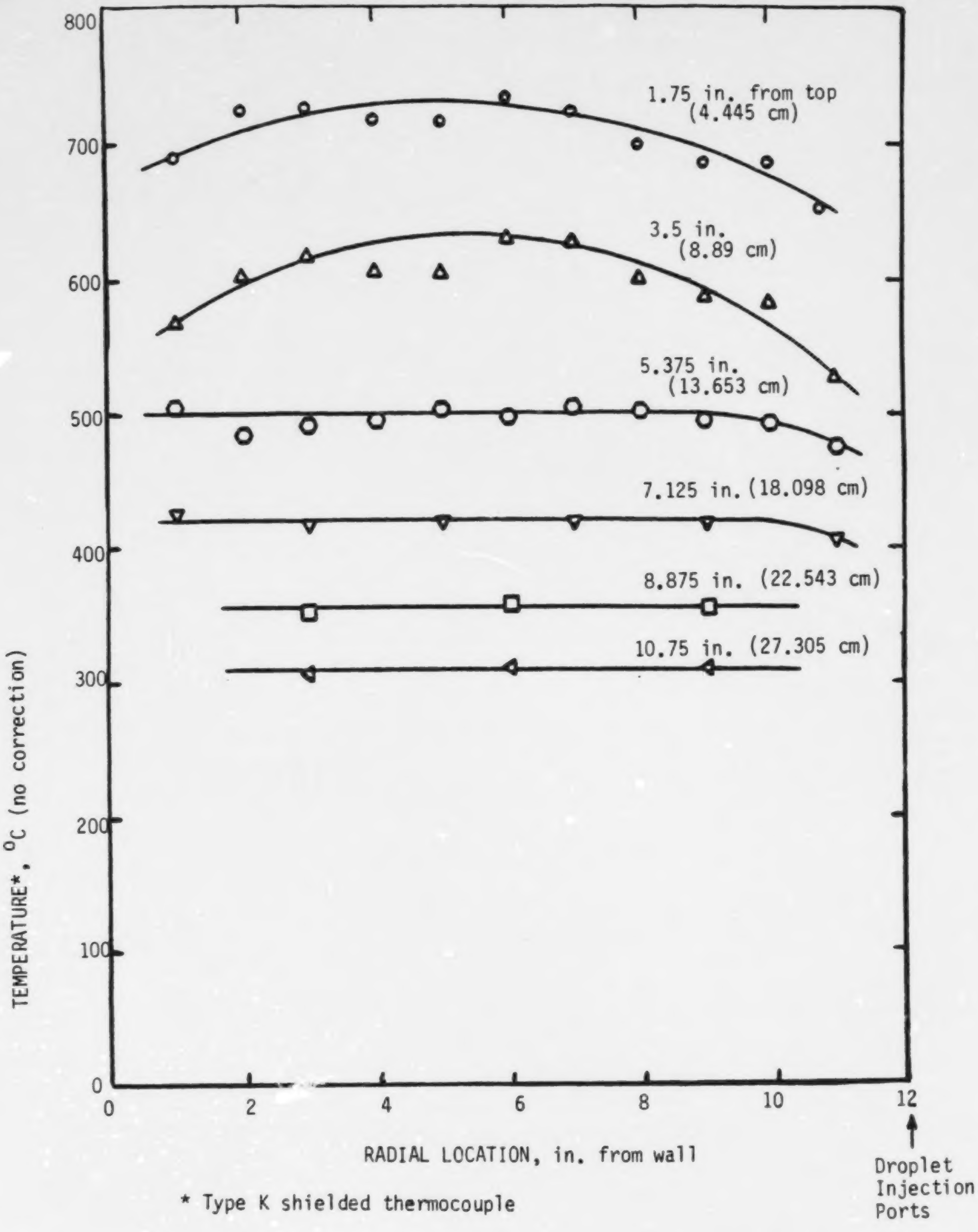
Approach

First the burner alone was characterized in terms of temperature and velocity fields; then droplets were injected at varying inlet conditions and droplet trajectories for both burning and nonburning cases were studied experimentally and modeled.

## 4.3 BURNER CHARACTERIZATION

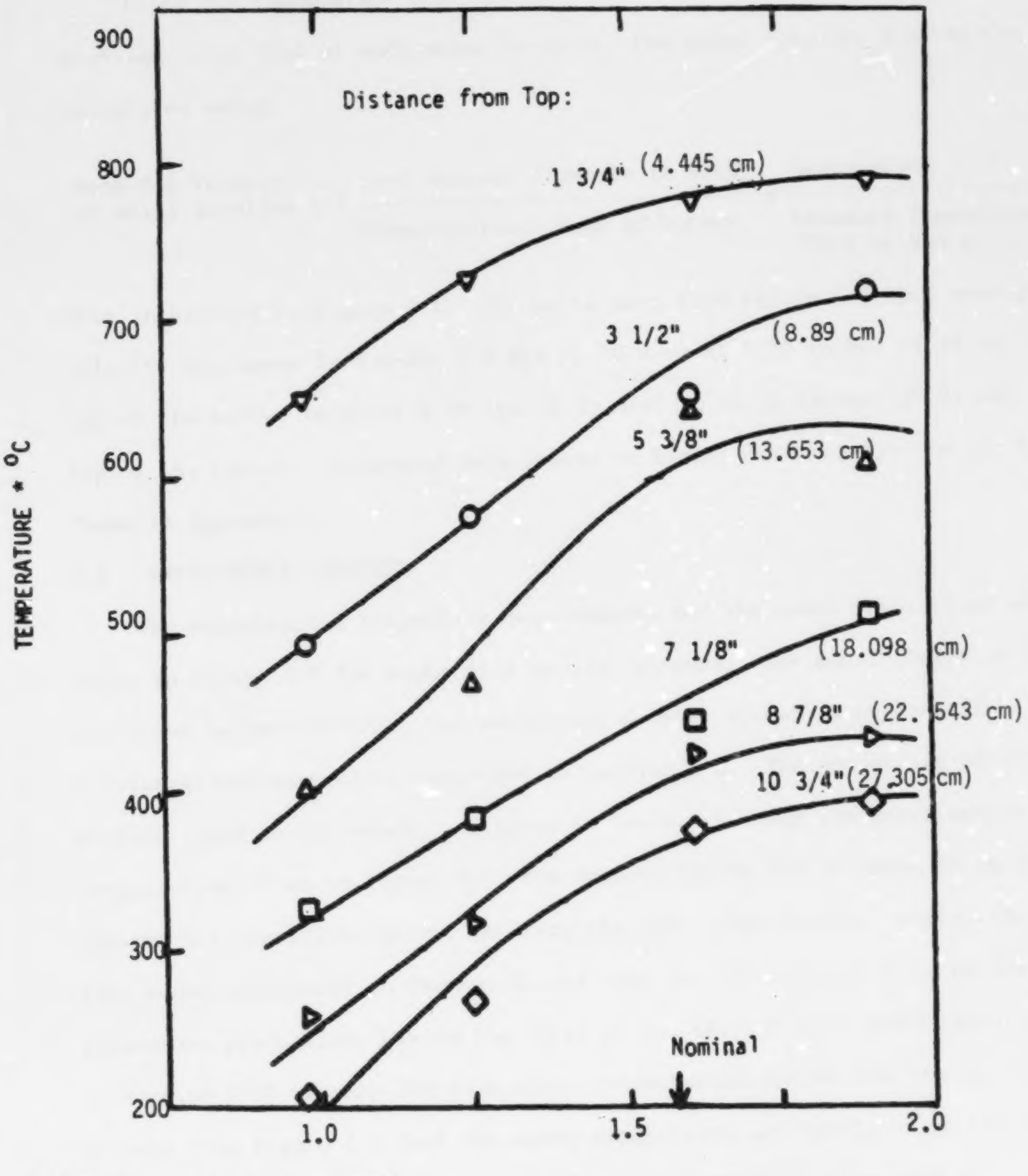
The burner was operated at 10 kBtu/hr and a stoichiometry of 1.575. The temperature profiles shown in Figure 4-2 were taken by inserting a Type K bare tip shielded thermocouple from the various injection ports on the burner and recording temperatures at various lateral locations. In Figure 4-2 it can be seen that near the flame at the top of the burner, the edge effects, due to wall cooling, on temperature profiles are evident. However, the temperature profiles become fairly uniform as the axial distance from the top of the burner becomes greater than about 5 inches. The peak temperature near the flame, at 1.75 inches from the top of the burner, was about 750°C and the temperature decreased to about 300°C as the axial distance became 10.75 inches.

Subsequently, the burner was fired at a load of 11 kBtu/hr but at stoichiometries of 0.99, 1.25, 1.59, and 1.9. Temperature measurements were made at each stoichiometry by a Type R bare tip thermocouple as explained before. The results at the axis of the burner for various axial distances and stoichiometries are plotted in Figure 4-3. Three observations can be made in Figure 4-3. First, the temperature at any stoichiometry decreases with increasing axial distance. Second, at any given axial location, the temperature increased with increase in stoichiometry possibly due to augmented heat transfer resulting from increased convection on increasing the air flow. Third, at the nominal stoichiometry of 1.575, the temperatures at the axis of



* Type K shielded thermocouple

**Figure 4-2. Radial temperature profiles in the flat-flame burner operated at 10 kBtu/hr** (2.931 W)



* Type R bare tip thermocouple

Figure 4-3: Temperatures in the Flat Flame Burner as a Function of Stoichiometry

the burner are higher in Figure 4-3 than those in Figure 4-2, perhaps due to increased load.

Using the temperature profiles in Figure 4-2, and assuming velocity profiles to be flat at each axial location, the axial velocity profile was calculated using:

$$\text{Mean Gas Velocity at axial location X} = \frac{\text{Fuel and air flowrate in SCFM}}{\text{Cross-section area of burner}} \times \frac{\text{Temperature at X}}{\text{Standard Temperature } (70^\circ\text{F or } 294\text{ K})}$$

This is plotted in Figure 4-4. It can be seen from Figure 4-4 that mean gas velocity decreases from about 0.6 fps (0.18 m/s) at 1.75 inches (4.45 cm) from top of the burner to about 0.35 fps (0.11 m/s) at 10.75 inches (27.31 cm) from top of the burner. Condensed data sheets on burner characterization can be found in Appendix C.

## 4.4 EXPERIMENTAL RESULTS

The experimental trajectory measurements and the model predictions are shown in Figure 4-5 for nonburning droplet streams. The model itself is explained in Section 5-3. The nonburning droplet streams were constituted of a water/glycerine mixture described in Section 3-3. The properties of this mixture, used in the model, are given in Table 4-1. For the experimental trajectories shown in Figure 4-5, the droplet had to travel about 10 cm in ambient air conditions before entering the flat flame burner. Hence, the cold flow model, discussed in Chapter 3, was used for the initial 10 cm of droplet trajectory prediction; beyond the first 10 cm, the hot flow model (explained in Section 5-3) was applied to predict trajectories inside the burner. It can be seen from Figure 4-5 that the model predictions are fairly close to experimental observations/measurements. The model also is capable of predicting trajectory spreads due to spacing effects, thus incorporating the interdroplet draft effects. The error bands shown in Figure 4-5 are based on

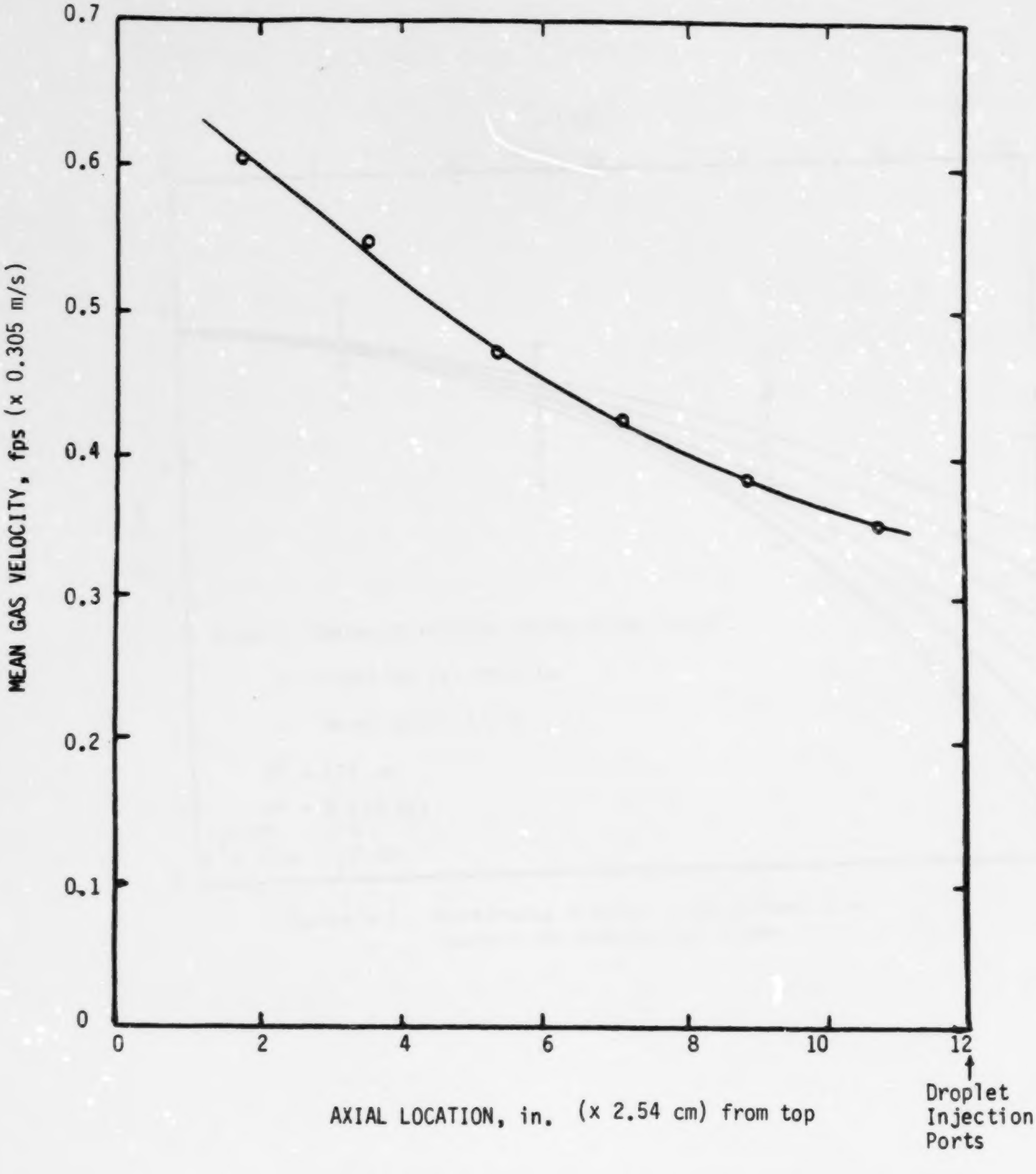


Figure 4-4. Velocity profile in the flat-flame burner

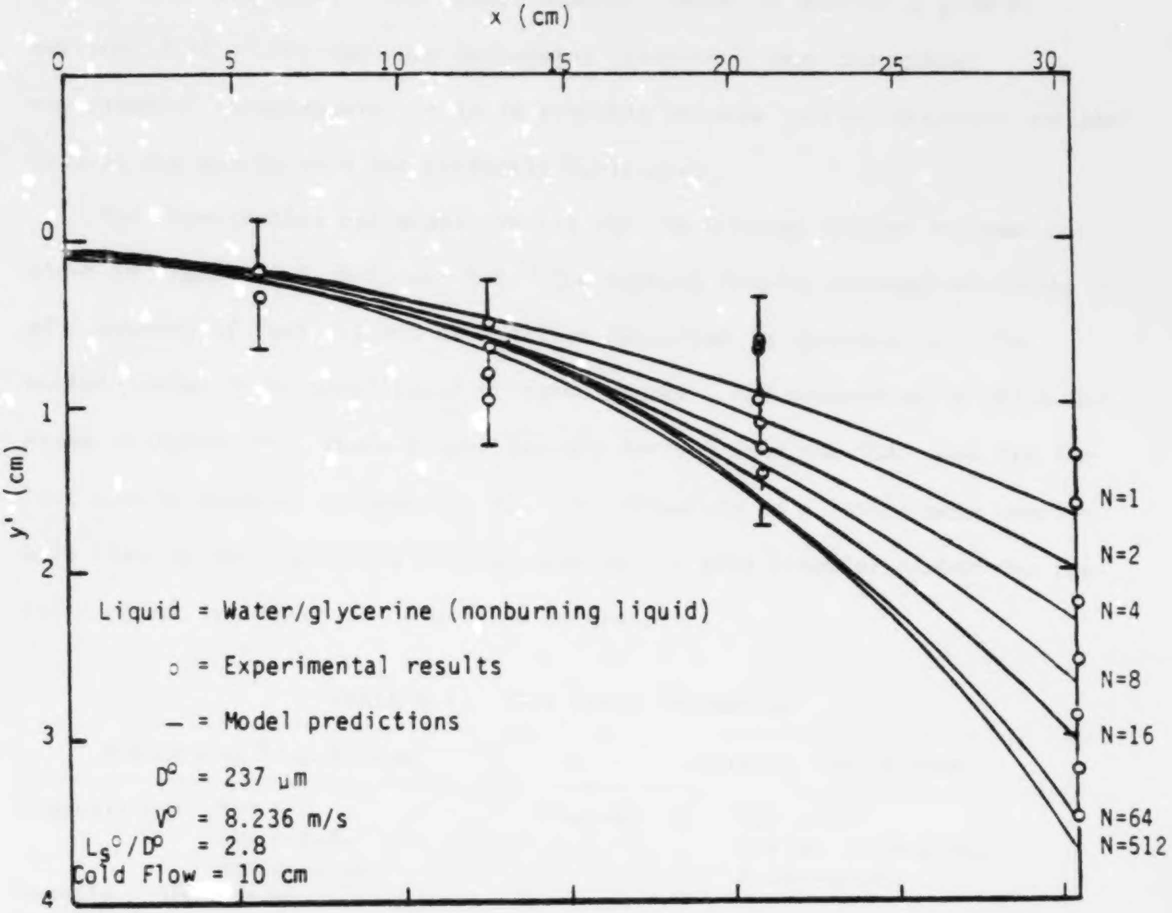


Figure 4-5. Nonburning droplet trajectories in a laminar two dimensional flame

the assumption that the uncertainty in visual measurement is about 1/8 inch (0.318 cm). Within these error bands, the droplet trajectories are well predicted by the model. The model, however, seems to predict a greater vertical fall y' for the same horizontal traverse x than the actual experimental measurements. This is probably because initial trajectories just leaving the nozzle were not perfectly horizontal.

The experimental and model results for the burning droplet streams are shown in Figures 4-6, 4-7, and 4-8. The burning droplet streams were made up of a mixture of fuel oil and an additive described in Appendix A5. The mixture seems to be constituted of three phases , the properties of which are shown in Table 4-1. These properties are derived from the TGA curve for the test liquid appended in Appendix A5. The situation is a little more complex here than in the nonburning droplet case as the mass transfer number for the third phase, $B_3$, needs to be modeled accurately.

TABLE 4-1. TEST FLUID PROPERTIES

Nonburning Drop Stream

Composition: 75% $H_2O$
25% $C_3H_8O_3$
Homogeneous
Density = 1060 kg/m$^3$
Boiling Point = 420 K
Specific heat = 3720 S/kg K
Latent Heat of Evaporation = 1.9440$^6$ S/kg
Heat of Combustion = 4.5x10$^6$ S/kg
$(A/F)_{th}$ = -/360

Burning Drop Stream

Composition: 80% ASA-3
20% No. 2 fuel oil
3 components

| | Fraction 1 | Fraction 2 | Fraction 3 |
|---|---|---|---|
| Mass Ratio | 0.85 | 0.1368 | 0.0132 |
| Density (kg/m$^3$) | 870 | 880 | 1500 |
| Boiling Point (K) | 430 | 523 | 800* |
| Specific Heat (S/kg K) | 1720 | 1890 | 1920 |
| Latent Heat of Evap. (S/kg) | 3.35x10$^5$ | 2.7x10$^5$ | --- |
| Heat of Comb. (S/kg) | 4.31x10$^7$ | 4.23x10$^7$ | --- |
| $(A/F)_{th}$ | 3.135 | 3.125 | --- |

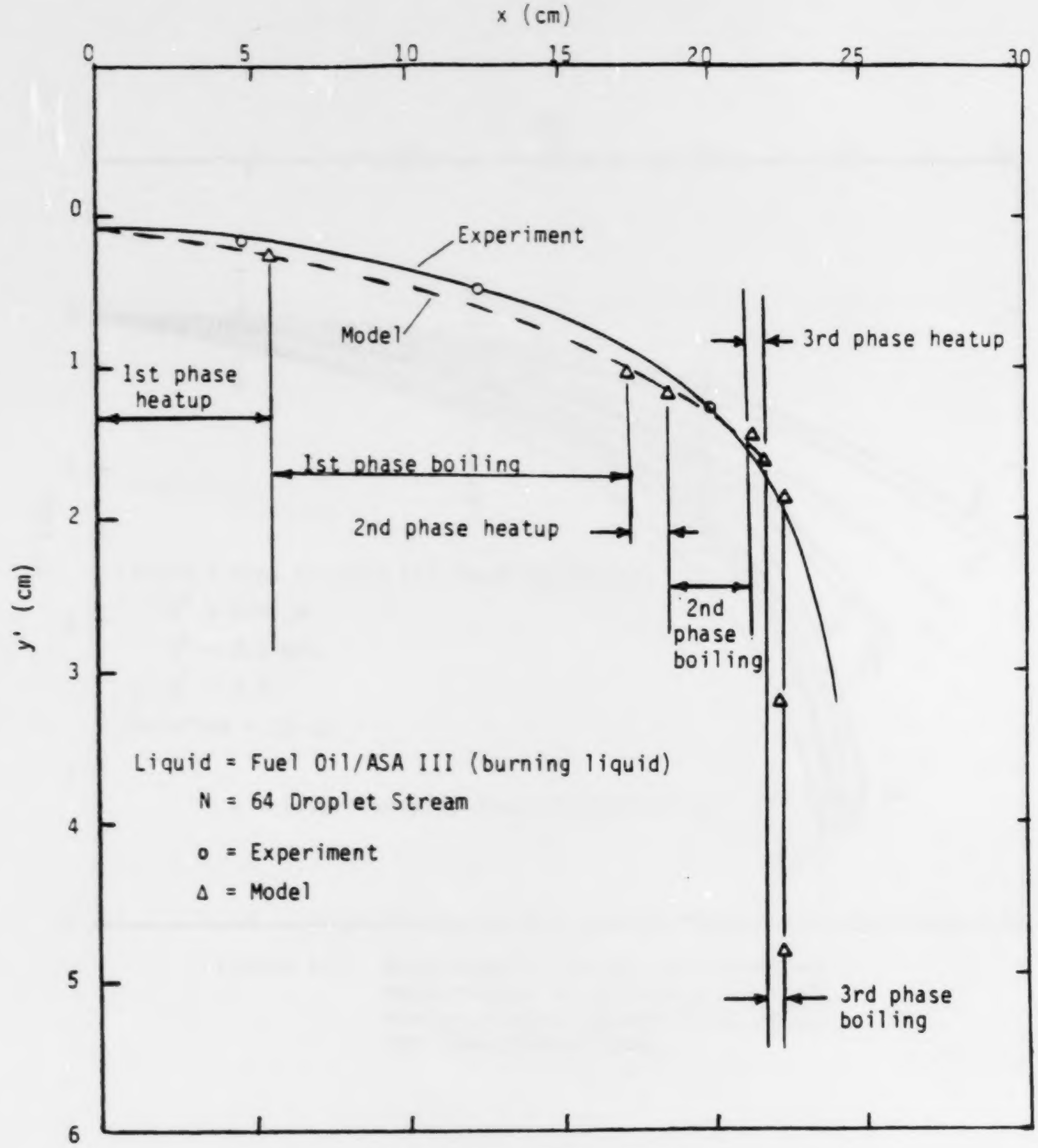


Figure 4-6. A burning droplet trajectory (N=64) in a laminar two dimensional flame.

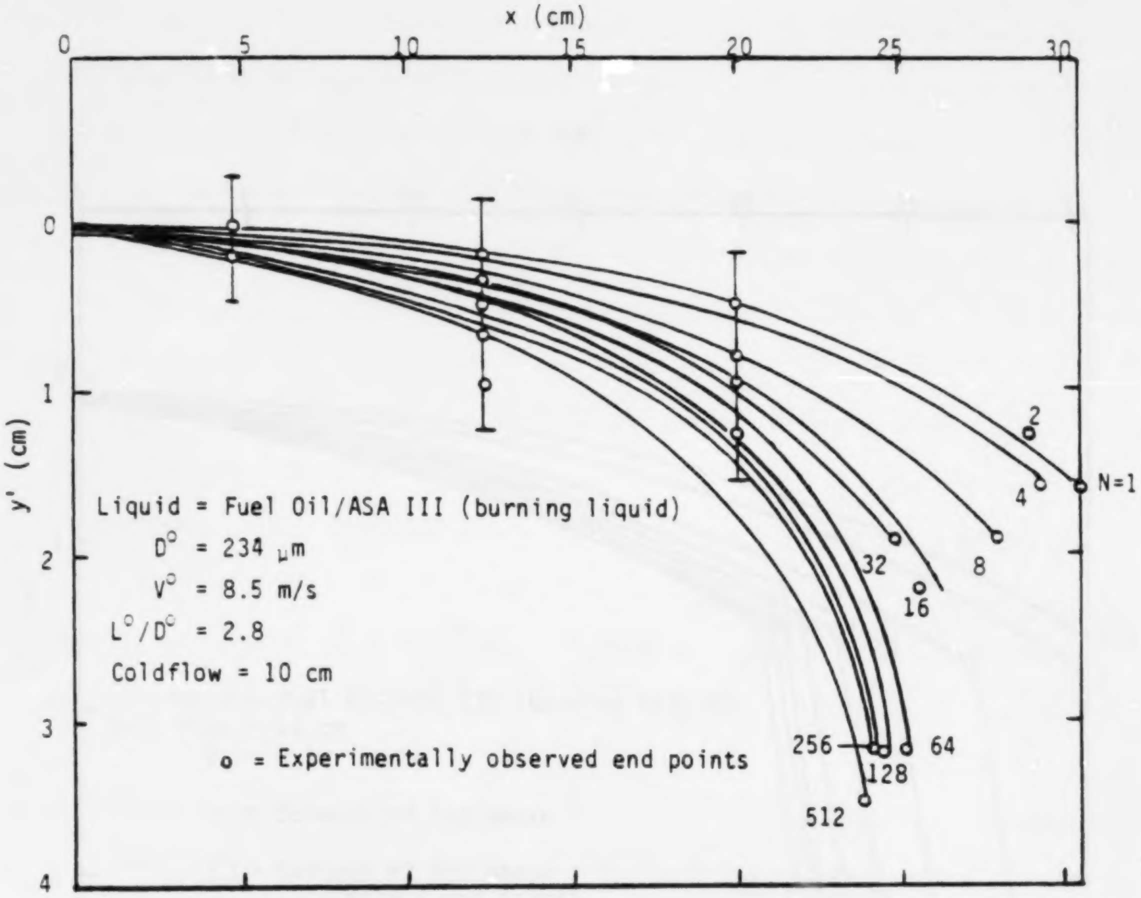


Figure 4-7. Experimental results for trajectory measurements of various differently spaced droplet streams in a laminar two dimensional flame.

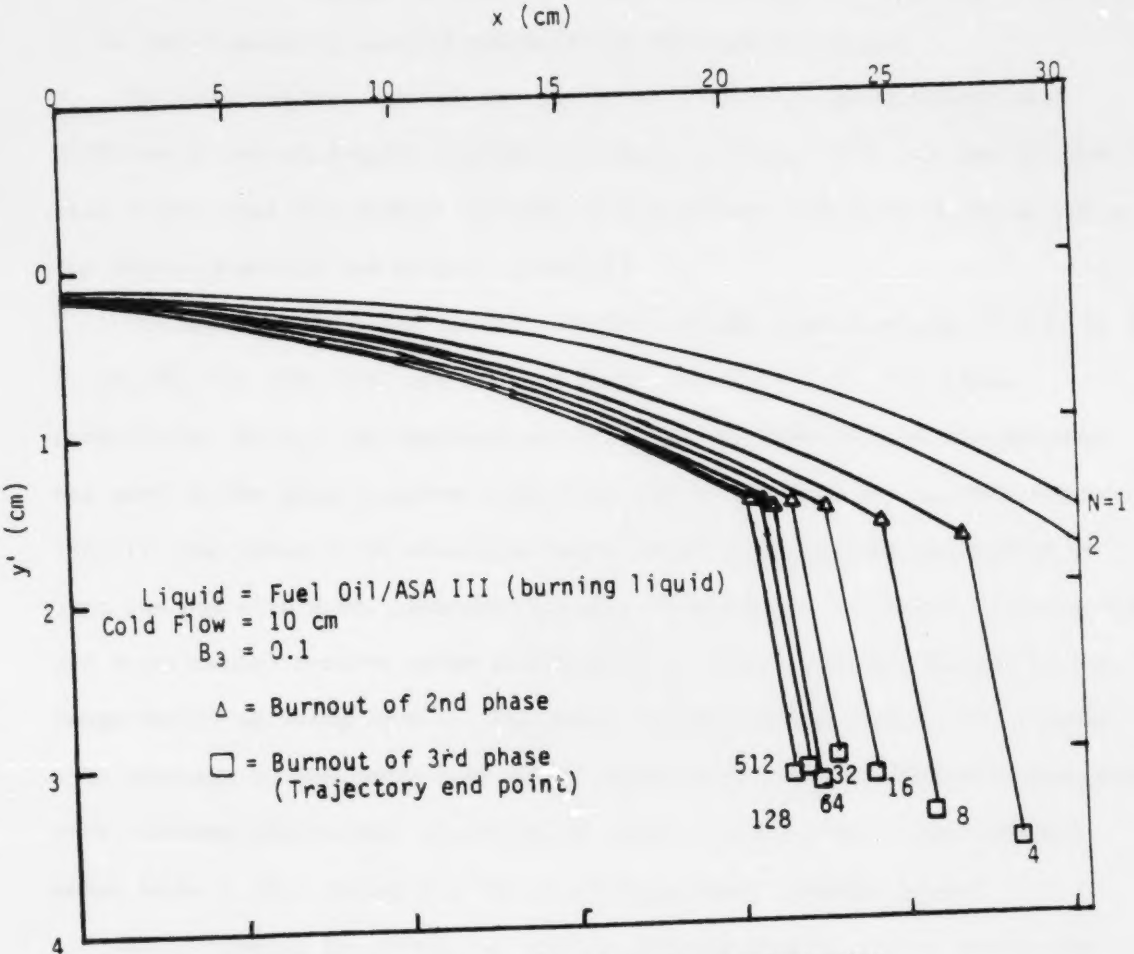


Figure 4-8. Model predictions for trajectories of various differently spaced droplet streams in a laminar two dimensional flame.

The experimental B model results for the case of burning droplet streams with N=64 are shown in Figure 4-6. It can be seen that the model with a $B_3$=0.1 predicts the trajectory closest to the experimentally measured one. It can also be seen that during third phase burning, the droplet is very small, and hence a small change in traverse x causes a large change in vertical fall y' as the droplet is carried downwards by the combustion gas.

The experimental results for the other trajectory measurements with differently spaced droplet streams are shown in Figure 4-7. It can be seen in this figure that the droplet streams with spacings of N=1, 2, 4, 8, and 16 are cut short, possibly due to wall quenching.

The model predictions for the droplet streams with spacings of N=1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 are shown in Figure 4-8. For these predictions, $B_3$=0.1 (as obtained earlier with the N=64 droplet stream case) was used as the mass transfer number for the third phase in the test liquid. Ideally, the value of $B_3$ should be based on all trajectories instead of on just the one with N=64. However, as seen from Figures 4-7 and 4-8, the model and experimental results agree fairly well for streams with spacings in the range 64-512 on using $B_3$=0.1. The model results, using $B_3$=0.1, for streams with spacings in the range 1-32 do not match with the experimentally measured ones, perhaps due to wall quenching of actual trajectories. Thus, $B_3$=0.1 seems to be a fair choice for the third phase mass transfer number.

While running the model for various burning droplet trajectories, the cold flow model (Section 3) was used to predict the droplets' trajectories during the first 10 cm of axial traverse.

The reduced data sheets for the nonburning and burning droplet stream cases and the computer programs used for model predictions are appended in Appendix D. The user information for using these programs is being presented to EPA in another report.

# SECTION 5

# TURBULENT DIFFUSION FLAME EXPERIMENTS AND RESULTS

## 5.1 INTRODUCTION

The trajectory and incineration of a droplet stream in a combustor is a function of droplet properties viz. size, velocity, droplet to droplet spacing, and droplets substance as well as the stream injection angle relative to the combustion flow field and the combustion flow field itself. Experiments were carefully designed and carried out to study the effect of above parameters on droplets' trajectories and incineration in a swirling, turbulent, diffusion flame. The results of trajectory measurements have been used to develop a three-dimensional numerical code capable of predicting droplet trajectories in a three-dimensional, swirling, turbulent, and combusting flow field.

## 5.2 EXPERIMENT

The objectives of this section were (1) to measure and predict the three-dimensional trajectories of single monodisperse droplet streams in turbulent, swirled combustion flow fields, and (2) to correlate these trajectories to droplet incineration effectiveness.

### Apparatus and Methods

The bench-scale combustion facility is shown in Figure 5-1. The 100 kW combustor has been described in Section 2.1 in detail. As mentioned before, the front wall contains a slot to allow off-axis droplet injection. A movable cooling coil for quenching the post-flame gases is shown.

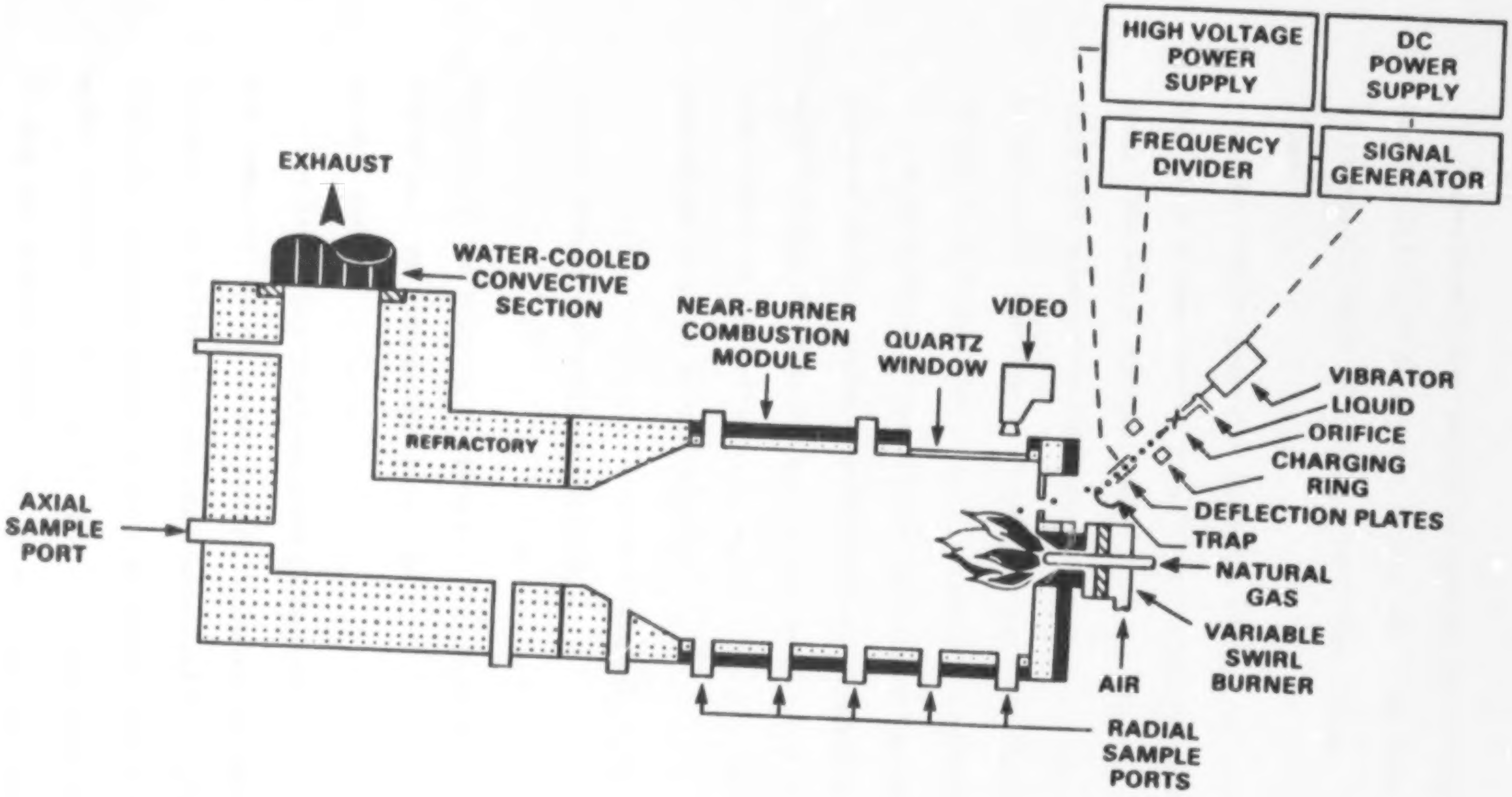

HIGH VOLTAGE POWER SUPPLY
DC POWER SUPPLY
FREQUENCY DIVIDER
SIGNAL GENERATOR
EXHAUST
WATER-COOLED CONVECTIVE SECTION
NEAR-BURNER COMBUSTION MODULE
QUARTZ WINDOW
VIDEO
VIBRATOR
LIQUID
ORIFICE
CHARGING RING
DEFLECTION PLATES
TRAP
NATURAL GAS
VARIABLE SWIRL BURNER
AIR
REFRACTORY
AXIAL SAMPLE PORT
RADIAL SAMPLE PORTS

Figure 5-1. Schematic of bench-scale combustion facility. The 50 cm internal diameter, 90 cm long near-burner combustion module is water-cooled and insulated with a 4 cm thick refractory lining. the IFRF burner has a movable-block air swirl generator and interchangeable fuel nozzles. The monodisperse droplet generator is shown with electronics for droplet separation. The water-cooled coil is shown in the combustor for quenching the combustion gases.

Experiments were mainly carried out on a natural gas Type C flame (see Section 2.1) with 30 percent excess air. The Type C flame, being most typical of practical, high-efficiency combustion systems, was used as the nominal flame.

The droplet generator assembly mounted on a swivel fixture (see Section 2.3) was located at a distance of approximately 14 cm from the burner axis. The swivel fixture permitted a variation in the angle of droplet injection relative to the combustor axis. A squared Plexiglas block was used to ensure the leveling of droplet stream relative to the horizontal datum thus making certain that the initial trajectories were horizontal for all streams.

Droplet diameter and droplet spacing in the uncharged stream, $L_s$, were measured directly using a strobescope to illuminate and freeze droplet images under a Nikon SMZ-2 microscope at the location of initial droplet separation (the center of the deflection plates). The initial droplet spacing after separation is given by the relation

$$L^{o} = L_{s} \times N.$$

Initial droplet velocity is given by

$$V^{o} = L_{s} \times f$$

where f is the vibrator frequency. One droplet is produced with each vibration. An independent measurement of liquid flow rate provided a mass balance check.

The trajectory starting point is defined as the droplet entry location to the combustor, 10 cm downstream of the center of the deflection plates. Therefore, to define the initial droplet velocity and spacing at the trajectory starting point, a two-dimensional cold flow model is used. This model, discussed in Section 3, determines how much the droplet slows down due to drag and gravity forces prior to entering the combustor. For a nonevaporating droplet, droplet spacing is related to droplet velocity by L/V = constant.

Radial profiles of temperature, velocity (three components), and species were measured at several radial and axial positions. Gas temperatures were measured by suction pyrometry (Appendix A6); axial, radial, and tangential velocity components were measured by using a specially designed five-hole pitot probe (water cooled with 0.8 cm uncooled tip, calibrated - see Appendix A7). "Instantaneous" velocities of the turbulent flow were recorded, allowing means and standard deviations to be calculated with a microcomputer. Radial profiles of axial velocity are consistent with overall mass balance.

The fluid that has been tested, chosen on the basis of conductivity (for electrostatic charging and deflection) and viscosity (for droplet formation), was a mixture of 80 percent (by volume) Shell Oil company fuel additive ASA-3, comprised mostly of xylene ($C_8H_{10}$), and 20 percent distillate fuel oil. The selection and properties of the test fluid are described in Appendix A5. Droplet trajectories were measured and recorded manually, with the aid of high speed photography. A continuous emissions monitoring system (CEMS), described in Appendix A8, was used to measure gaseous effluent. Specifically, hydrocarbon destruction efficiency was determined by measuring the increase in exhaust unburned hydrocarbons (surrogate POHC), UHC, and carbon monoxide (PIC), CO, with droplet injection over the levels without droplet injection. These emission measurements were taken from the stack where the combustion gases are well mixed. Flame ionization was used to detect UHC, and an infrared instrument was used for CO measurement. A removable water-cooled coil for quenching the combustion gases was located nominally at 41 cm into the furnace, well downstream of the Type C flame. This resulted in a bulk gas residence time of 0.6 seconds before quenching. The quench coil provided a means of adjusting the effective refractory wall volume to simulate actual droplet post-flame residence times before cold wall impingement.

A quality assurance/quality control QA/QC plan was prepared under this contract to ensure that the data quality was within acceptable limits.

Approach

Baseline measurements (i.e., no droplet injection) of combustion gas temperature and velocity were done first. The quench coil was completely removed from the combustor for these measurements. Then droplet trajectories were observed for a variety of initial droplet stream conditions, including variation in droplet size, velocity, spacing, and injection angle. These measurements were also taken without the quench coil inserted. Model development ensued, with droplet interactions and turbulence effects being considered. Finally, droplet incineration measurements were made with the quench coil located at 41 cm.

## 5.3 DROPLET TRAJECTORY RESULTS

In the cylindrical polar coordinates system used, x is the axial coordinate, r is the radial coordinate, and $\theta$ is the angular coordinate, defined as zero in the horizontal plane and 90 degrees at the top of the combustor. The coordinate system is shown in Figure 5-1a.

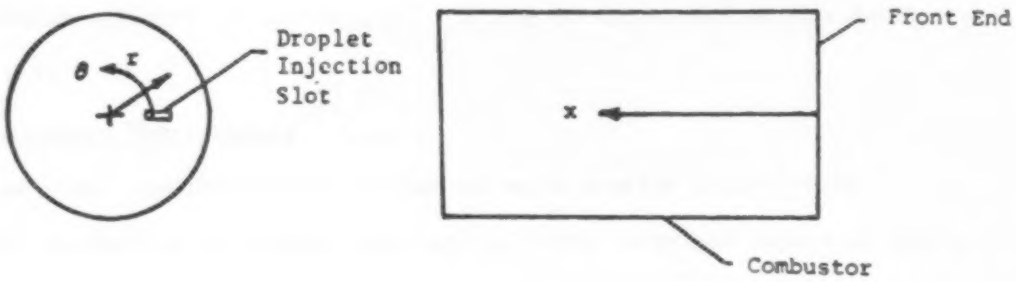


Figure 5-1a. Polar coordinate system used to measure droplet trajectories in the combustor

## Type C Flame Characterization

A peak flame temperature of 1750 K was measured at the combustor centerline, near the tip of the visible flame, with temperatures decreasing to approximately 1100 K at the wall (Figure 5-2). Axial symmetry was observed.

Figure 5-3 exhibits maps of the mean axial, radial, and tangential velocity components in the near-burner zone. At each point there is actually a distribution of velocities over time due to turbulent fluctuations in the reacting flow. Standard deviations of velocity were in the range of 1 to 5 m/s, often exceeding 50 percent of the mean velocity. The axial velocity map shows strong internal recirculation within the flame (indicated by negative velocities), as well as external recirculation near the combustor walls. Peak velocities of greater than 25 m/s were measured near the burner quarl exit, consistent with the input air velocity at the burner throat of 28 m/s. The calculated bulk mean axial velocity, approximately 2.6 m/s, is approached beyond the 50 cm axial distance.

Mean radial velocities were found never to exceed 8 m/s. Very little radial motion of the combustion gases was seen beyond the 215 cm axial location. Mean tangential velocities were found to be negative, consistent with the direction of swirl. A strong degree of swirl was observed near the burner quarl exit, with the swirl mostly dissipated by 40 cm downstream. The peak tangential velocity of approximately 12 m/s is consistent with a swirl number of 1.3.

## Droplet Trajectory Measurements

Fourteen test conditions were evaluated, with droplet trajectories measured for variations in droplet spacing, velocity, size and injection angle (Table 5-1).

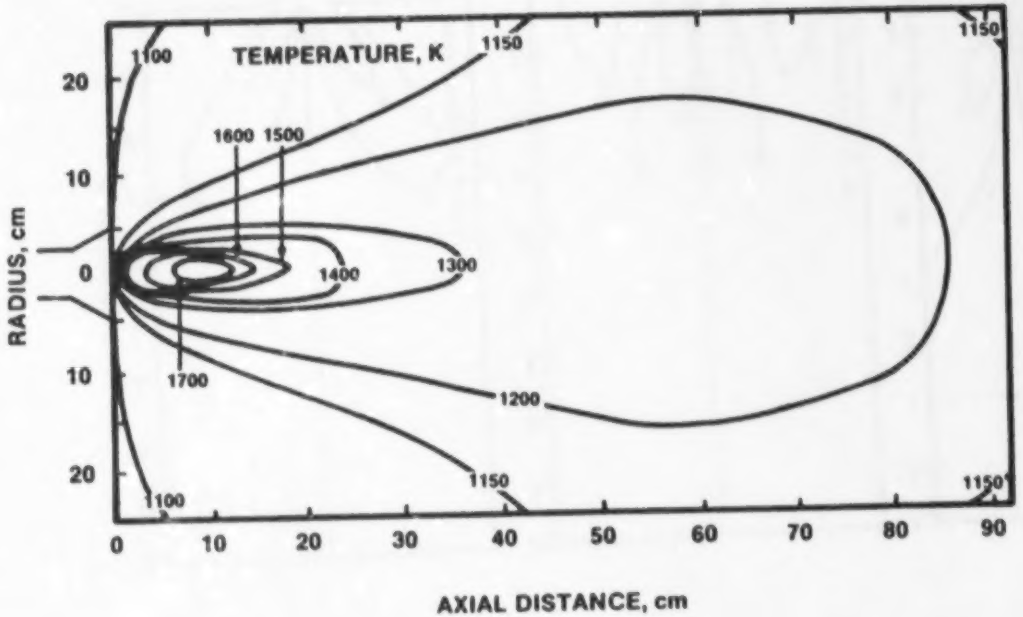


Figure 5-2. Near-burner zone isotherms for Type C flame baseline. This thermal map is constructed from axial and radial temperature profiles. Symmetry about the centerline axis was verified with a limited number of measurements and is assumed for the entire field.

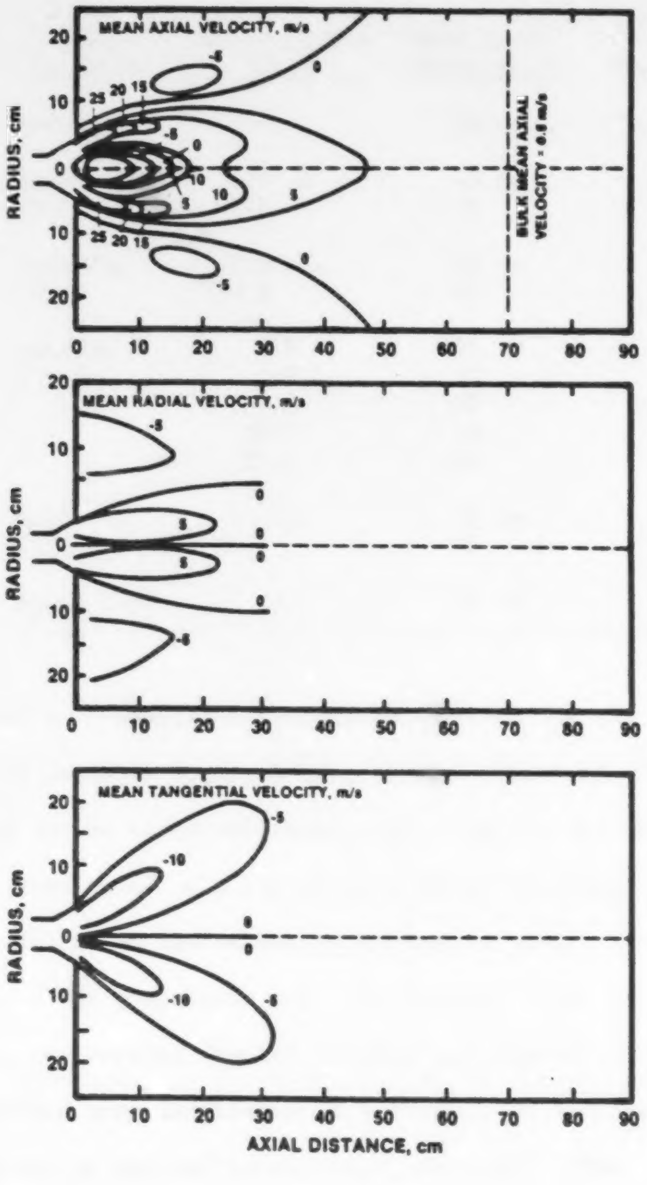


Figure 5-3. Near-burner field velocity maps for Type C flame baseline. The lines of constant velocity are constructed from three-dimensional axial and radial velocity profiles. Symmetry about the centerline axis was verified and is assumed for the entire field.

TABLE 5-1. DROPLET INJECTION CONDITIONS AND MEAN AXIAL PENETRATION

| Test Variable | Test Variable Value | Mean Axial Penetration | Initial Model Prediction |
|---|---|---|---|
| Nominal | --- | 30 cm | 23 cm |
| Size | 297 m | 45 cm | 33 cm |
| ($D^o$) | 378 | 55 | 50 |
| Velocity | 3.8 m/s | 20 cm | 18 cm |
| ($V^o$) | 9.8 | 45 | 25 |
| Spacing | 2.5 | 55 cm | * |
| ($L^o/D^o$) | 4.7 | 45 | * |
| | 8.8 | 35 | * |
| | 16.7 | 30 | * |
| | 32.3 | 30 | * |
| Angle | 0 deg. | 30 cm | 18 cm |
| ($\Theta$) | 45 | 35 | 28 |
| Flame Type | A | 25 cm | * |

The domain of droplet trajectories observed for the nominal test conditions is shown in Figure 5-4 in the two planes of observation. Superimposed on the cross-sectional view along the centerline axis are lines of constant mean axial velocity of the combustion gases. The droplets were observed to follow an approximately common path until they entered the high shear layer of the combustion gas. The burning times were very short, as indicated in the burning droplet "flecks" stretching only a few centimeters. The large shaded area denotes the distribution of burning droplets, igniting and burning out at various locations in the area. Thus, there is no single trajectory that describes the test condition. The existence of a domain of droplet stream burnout locations rather than a single burnout point suggests that either the droplet injection properties are nonuniform or the gas flowfield fluctuates with time (i.e., turbulence). Uniformity of droplet formation and injection was carefully monitored during testing. Therefore,

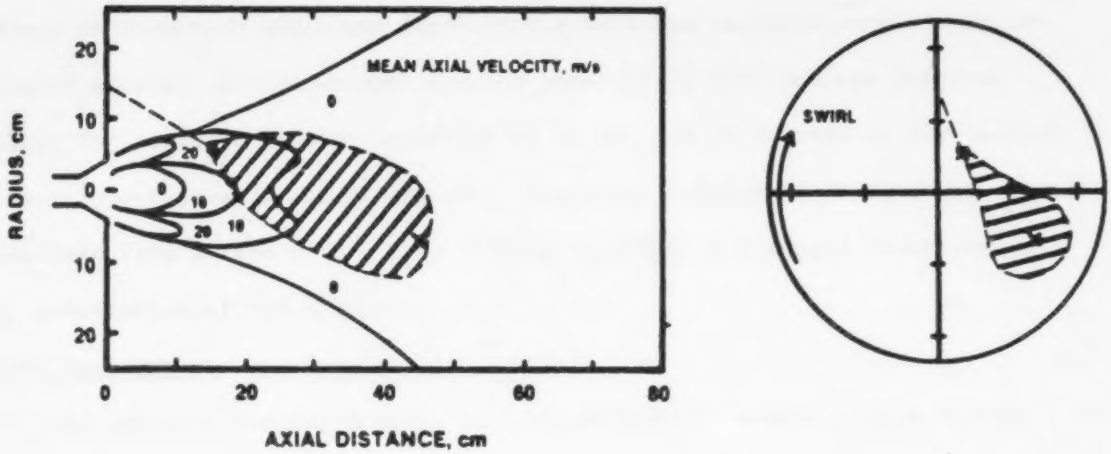


Figure 5-4. Droplet trajectory for the nominal test condition. The domain of droplet burnout locations is shown by the shaded area. an axial velocity profile is superimposed in the top view drawing.

the range of trajectories observed in the experiment is attributed to high combustion gas turbulence. The large velocity fluctuations that were measured support this hypothesis.

Measured mean axial droplet penetration distances are listed in Table 5-1. Closely spaced droplets penetrate farther than isolated droplets. Little effect of spacing was observed for values of greater than 20 diameters. Axial penetration roughly doubles for a doubling of initial droplet velocity. Axial penetration increases as droplet diameter increases, as well. The effect of injection angle was observed for both the isolated droplet and the droplet stream. Little change in axial penetration distance was observed either for isolated droplet injection at 0, 30, and 45 degrees or for droplet stream injection at 0 and 30 degrees. Finally, a change in the combustion gas flowfield from a Type C to a Type A flame resulted in a slight reduction in the penetration of the droplet.

## Model Development

The isolated burning droplet ballistics model(6) was run, with Type C flame baseline data and droplet injection parameters as model inputs. The predicted axial location at which the droplet is completely evaporated is compared to the measured mean axial penetration (Table 5-1). While the predicted radial and circumferential distances travelled before complete droplet evaporation closely agree with experimental results, the model predictions are all less than the axial penetrations observed in the experiment. However, predicted trends match those measured experimentally for droplet injection size, velocity, and angle.

To better predict the experimental results two areas of model development were identified. First, droplet spacing effects had to be modeled in terms of drag and burning rate influences (discussed in Sections 3 and 4). Second, gas flowfield turbulence effects had to be modeled to predict the distribution of trajectories observed (Figure 5-4).

Model Description

The simple, numerical model for predicting the ballistics of an isolated burning droplet(6) has been refined to include effects of droplet interaction on drag and evaporation rate, evaporation effects on drag and turbulence effects on penetration. The model is used to solve the uncoupled equations of droplet motion in a Lagragian framework. A three-dimensional grid structure is established for specifying the background gas velocity ($V_g$), temperature ($T_g$), and chemical speciation. Calculations are terminated when the droplet exits the computational domain.

Drag and gravitational forces are to be the only external forces on the droplet.

The drag force, $F_D$, has two vector components ($F_{D1}$ and $F_{D2}$). The drag coefficient with droplet spacing effects ($C_D$) is applied to the drag component in the droplet stream direction; the drag coefficient without spacing effects ($C_D^{\circ}$) is applied to the other drag component. $F_{D1}$ is defined to be aligned with the droplet velocity vector, $V_d$; $F_{D2}$ is then perpendicular to the plane containing $V_g$ and $V_d$ (Figure 5-5). The magnitude of the force vectors are given by:

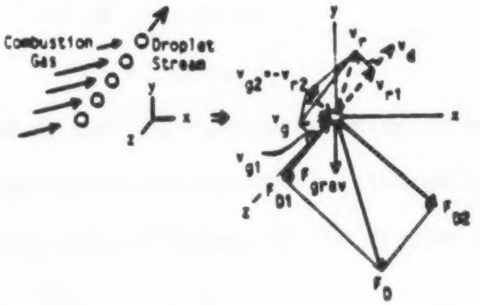


Figure 5-5. Vector diagram in three dimensions. Velocities shown with dotted lines; forces shown with solid lines.

$$|F_{D1}| = C_D{*} \frac{\rho_a A}{2} v_{r1} \qquad (5\text{-}1)$$

$$|F_{D2}| = C_D{*} \frac{\rho_a A}{2} v_{r2}$$

where $v_{r1}$ is the component of relative velocity ($v_r = V_d - V_g$) aligned with $V_d$ and $v_{r2} = v_r - v_{r1}$. The evaporating droplet drag coefficient (* denotes mass transfer) has been determined by Eisenklam, et al.(31) Evaporation has been found to decrease drag by a factor $n_e$ ($n_e = C_D{*}/C_n$), given by:

$$n_e = 1/(1 + B) \qquad (5\text{-}2)$$

where B is the mass transfer number, defined by Equation 5-5c. Force balance yields:

$$\Sigma F_x = ma_x = F_{D1x} + F_{D2x} \qquad (5\text{-}3)$$

$$\Sigma F_y = ma_y = F_{D1y} + F_{D2y} + F_{grav}$$

$$\Sigma F_z = ma_z = F_{D1z} + F_{D2z}$$

where $F_{grav}$ is the gravitational force (= $-mg$).

Heat and mass transfer are modeled in two steps: droplet heating to the liquid boiling point, followed by droplet evaporation. During droplet heating, its diameter is assumed to be constant (i.e., no evaporation), and its temperature (T) is assumed to be uniform (i.e., low Biot number). Here, the time rate of change of the droplet temperature is given by:

$$\frac{dT}{dt} = 6 \frac{Nu\ k_g}{D^2 c_{p_\ell} \rho_\ell} [T^\infty - T] \qquad (5\text{-}4)$$

where the Nusselt number (Nu) is calculated using an empirical relation.(32) After the droplet temperature reaches the boiling point, evaporation begins. In this stage, the time rate of change of the droplet diameter is given by:

$$\frac{dD}{dt} = - C_B \frac{1}{2D} [1 + 0.23\ Re^{0.5}]\ n_s \qquad (5\text{-}5a)$$

where the evaporation constant ($C_B$) is given by:

$$C_B = \frac{8\ k_g}{c_{p_\ell} \rho_\ell} \ln(1+B) \qquad (5\text{-}5b)$$

and where the mass transfer number (B) is given by:

$$B = \frac{c_{p_\ell}(T^\infty - T)}{L} + \frac{Q\ Y_O^\infty}{\sigma L} \qquad (5\text{-}5c)$$

Here, $k_g$, $\rho_\ell$, and $c_{p_\ell}$ are properties of the liquid and background gas, Q is the heat of combustion of the droplet, L is the latent heat of vaporization, $Y_O^\infty$ is the mass fraction of the oxidizer in the background gas, and $\sigma$ is the oxidizer-to-fuel mass ratio. The effect of multiple droplet interaction on evaporation rate, accounted for by $n_s$, has been quantified by Labowsky(28):

$$n_s = 1 - (2L/D)^{-1} + (2L/D)^{-2} \qquad (5\text{-}6)$$

Turbulence effects on droplet dispersion are modeled via the stochastic approach proposed by Dukowicz.(33) By this "discrete droplet" method the gas turbulence is randomly sampled during each droplet's flight and allowed to influence its motion. The total stream behavior is obtained by averaging over a large number of droplets. The number of droplet paths simulated is determined statistically, with the number being sufficient to describe a distribution of trajectory endpoints.

## Final Model Results

The three dimensional model results with a third phase mass transfer number of $B_3$=0.10 and including the effects of turbulence are shown in Figures 5-6, 5-7, 5-8, and 5-9. Also depicted on these figures are the experimentally measured results.

Figure 5-6 shows the effect of initial droplet size on axial penetration along the combustor. Both the experimental measurements and model predictions indicate that the axial penetration of a droplet in a combustion flow field increases with the droplet's size. Model predictions corresponding to the

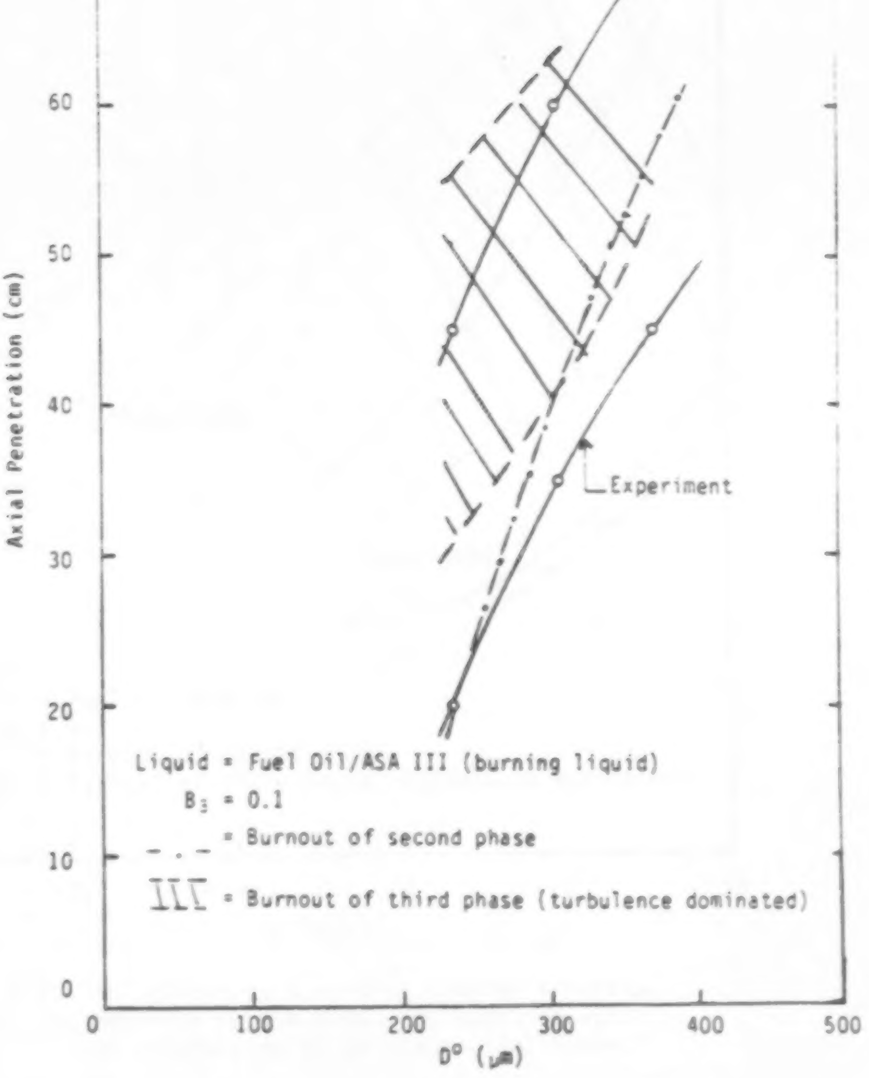


Figure 5-6. The effect of a burning droplet's initial size on the droplet's axial penetration in a turbulent three dimensional flame.

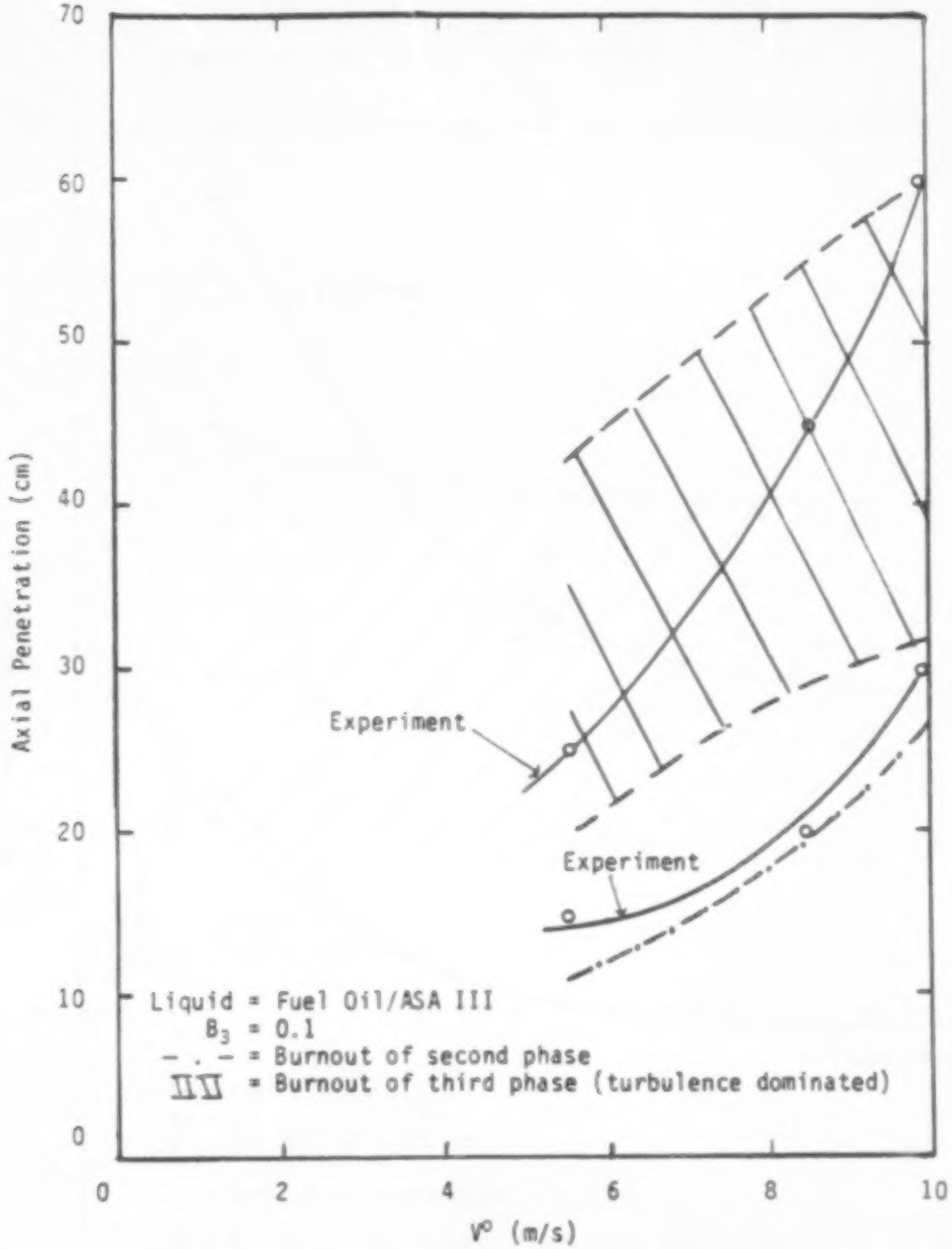


Figure 5-7. The effect of a burning droplet's initial velocity on the droplet's axial penetration in a turbulent three dimensional flame.

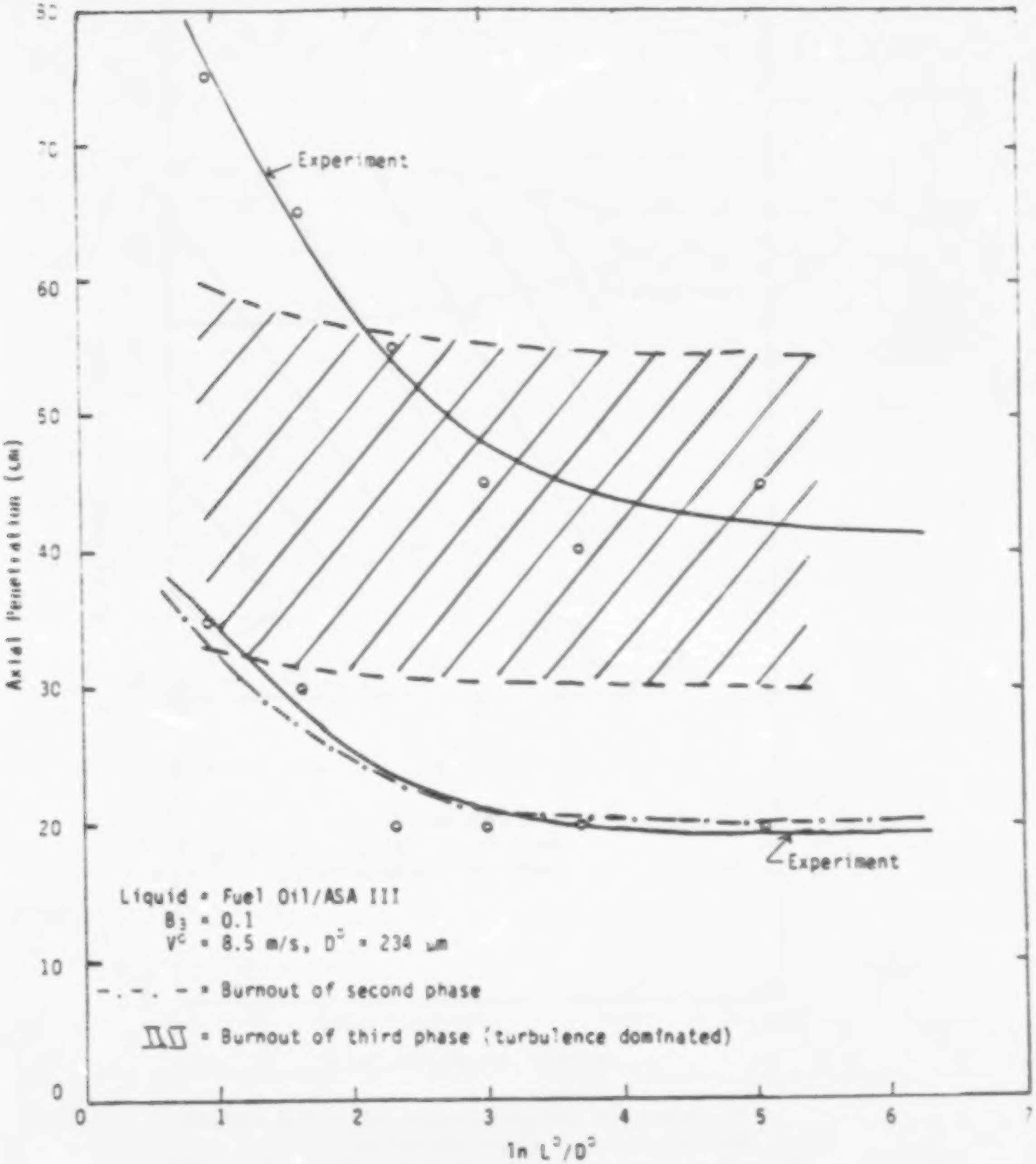


Figure 5-8. The effect of droplet's initial spacing in a burning droplet stream on the axial penetration in a turbulent three dimensional flame.

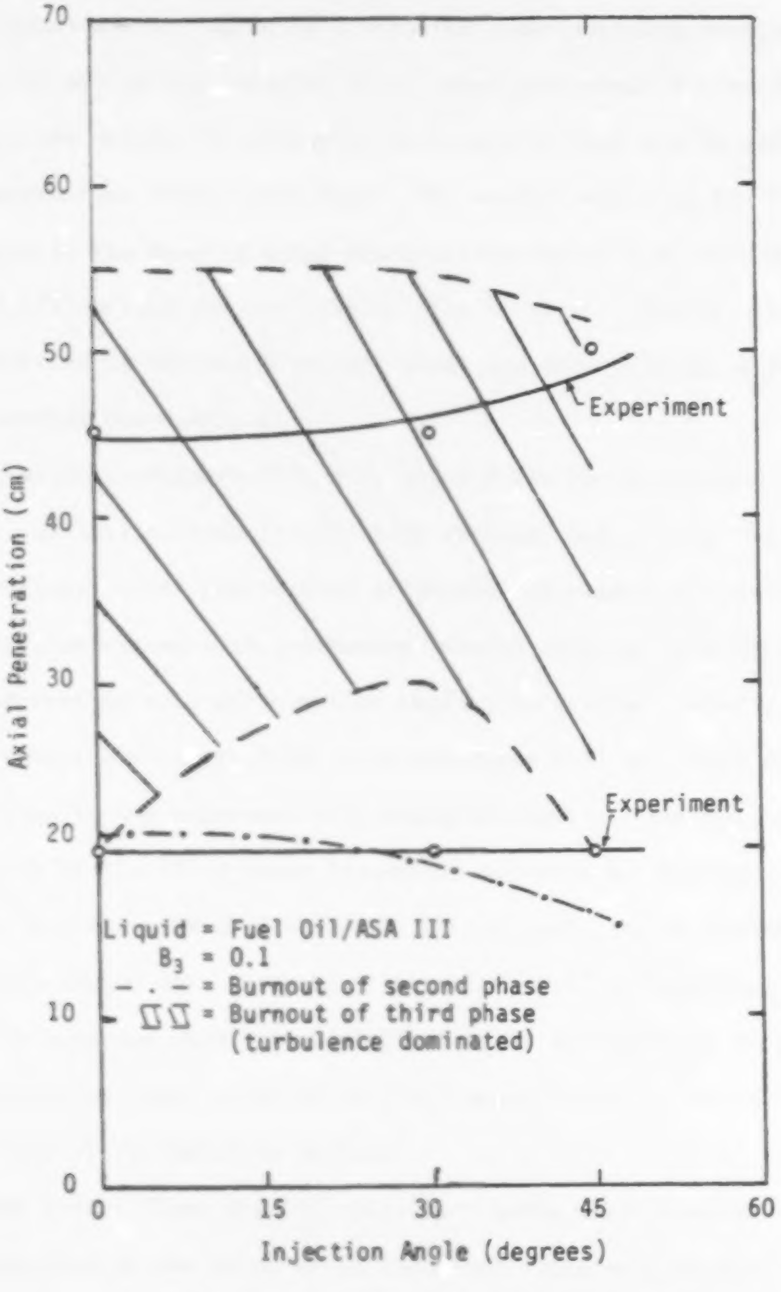


Figure 5-9. The effect droplet stream's injection angle relative to combustion flow field on the droplet's axial penetration in a turbulent three dimensional flame.

droplet axial position when phase 2 has boiled off and just phase 3 remains in the droplet matter, agree well with the experimentally measured lower range number at any initial droplet size. When just phase 3 remains in the droplet matter, the droplet is probably very small in size and is affected greatly by combustion flow field turbulence. The shaded region in the Figure 5-6 pertains to the band of axial penetrations where final burnout (third phase boiler off) occurs for any initial droplet size. Clearly, the burnout region as predicted by the model is very large and this finding conforms with the experimental observations.

Similarly, Figures 5-7, 5-8, and 5-9 can be interpreted to examine the effects of initial velocity, initial spacing, and initial angle on the axial penetration. Axial penetration of droplet increases with increasing initial velocity, decreases with increasing initial spacing, and increases slightly with increasing initial injection angle. In general, model predictions for axial penetration pertaining to second phase boil off state of the droplet are very close to the experimentally measured results. However, turbulence modelling of the third phase trajectory needs to be improved. Also, spacing effects are not predicted very well by the model in its present state.

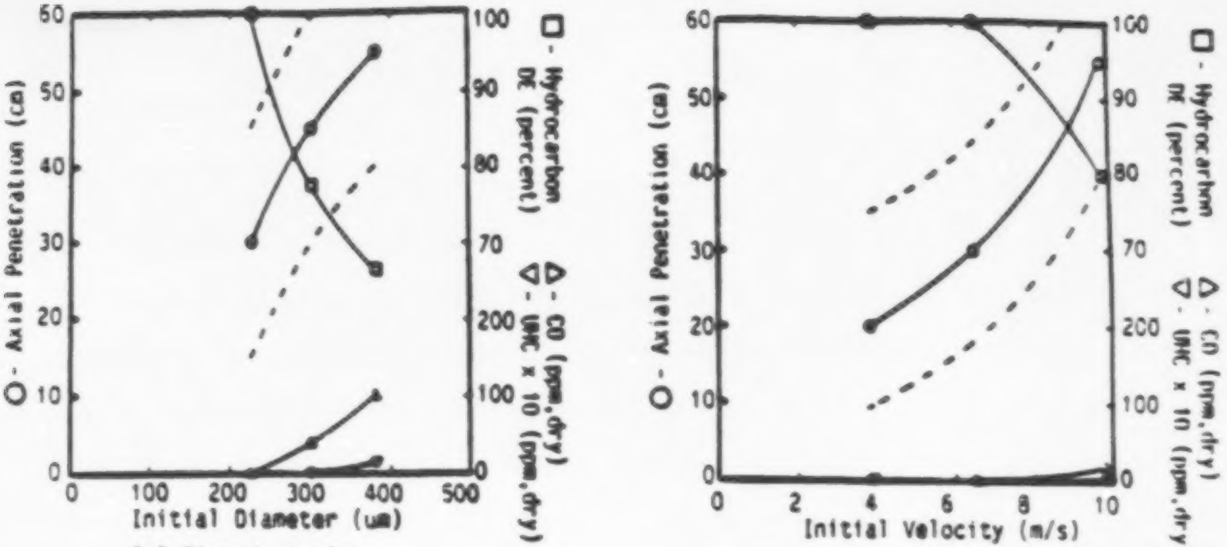
The reduced data pertaining to turbulent flow field measurements and the computer programs used for model predictions are appended in Appendix E. User information on these programs will be issued by EPA in another report.

## 5.4 DROPLET INCINERATION RESULTS

The Type C flame droplet trajectory tests were repeated with the quench coil inserted at the 41 cm axial location. This coil reduced the bulk combustion gas temperature by 200 to 300 K, cooling the entire gas flow to less than 1100 K. The gases were well mixed prior to extraction for gas species analysis. The emissions were analyzed without droplet injection (baseline condition), then with droplet injection, and again without droplet injection. The change in exhaust CO and UHC levels was noted, with hydrocarbon destruction efficiency being calculated based on the mass of carbon emitted as CO and UHC divided by the mass of carbon injected in the droplets. The nominal droplet condition was a 225 μm diameter droplet injected with a 6.5 m/s velocity, with a spacing of 130 droplet diameters, and at an angle of 30° from axial toward the burner centerline.

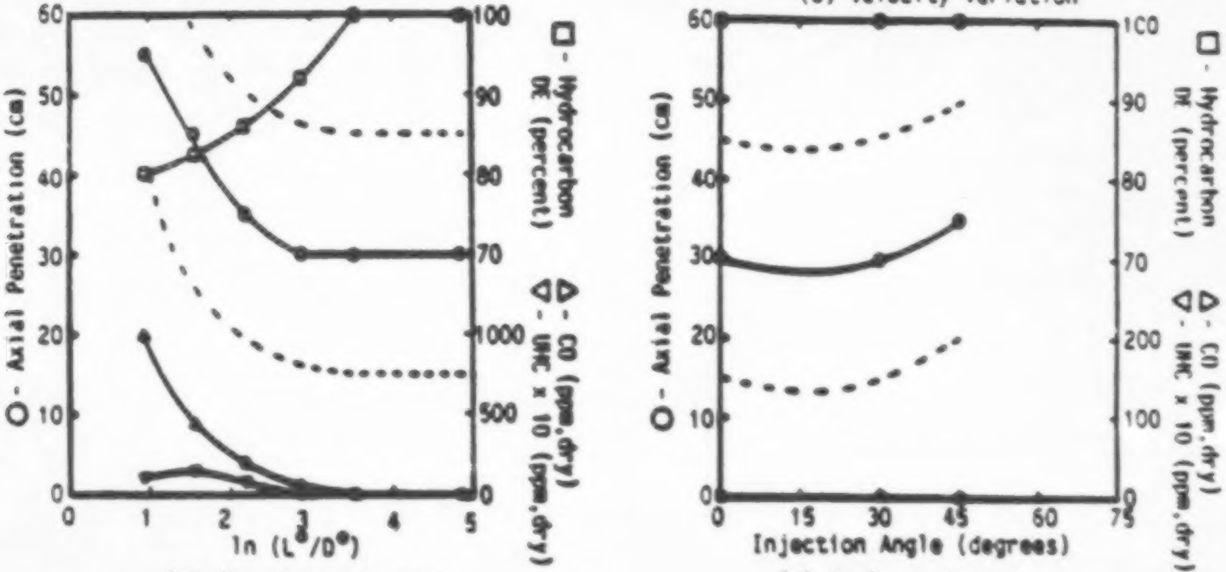
Results are shown in Figure 5-10. The previously measured mean axial penetration is shown, with dotted lines representing the range of droplet trajectories. For the nominal test condition the hydrocarbon in the injected droplet was completely destroyed. However, as initial droplet diameter increased to almost 400 μm, droplet hydrocarbon destruction efficiency decreased to less than 70 percent and the mean axial penetration increased to 55 cm (Figure 5-10a). Similarly, as initial droplet velocity increased from 4 to 10 m/s, mean axial penetration increased from 20 to 55 cm and droplet hydrocarbon destruction efficiency decreased from 100 to 80 percent (Figure 5-10b). In Figure 5-10c, the correlation of mean axial penetration and hydrocarbon destruction efficiency is observed for initial droplet spacing variation. As initial droplet spacing decreases, axial penetration increases and hydrocarbon destruction efficiency decreases. In Figure 5-10d, it is shown that droplet injection angle had little effect on either droplet penetration or hydrocarbon destruction efficiency.

The incineration data indicate that droplet hydrocarbon destruction efficiency is related inversely to droplet penetration, which depends on droplet atomization properties. Though uncertainty in the droplet hydrocarbon destruction efficiency is large (about 5 percent) due to the small droplet feed rate relative to the natural gas feed rate, the data indicate that destruction of the hazardous components of rogue droplets may be difficult and that potential incinerator failure modes exist due to incomplete combustion of



(a) Size Variation

(b) Velocity variation



(c) Spacing variation

(d) Angle variation

Figure 5-10. **Comparison of droplet mean axial penetration and droplet carbon destruction efficiency**

rogue droplets. Thus, predicting rogue droplet ballistics may be an important tool for anticipating incinerator failure modes due to poor atomization.

# SECTION 6

# QUALITY CONTROL EVALUATION REPORT

## 6.1 INTRODUCTION

The quality assurance objectives of this project were to assure that 1) the experimental conditions used were representative of the intended experimental design, and 2) the collected data were accurate and useful. The QA/QC procedures documented in the Quality Assurance Project Plan required that all continuous monitors and other measurement instruments, where possible, be carefully calibrated using manufacturer's procedures or other published methods. Zero and span checks were performed each test day on the continuous monitors. Annual calibrations of air flow and gas flow devices were also performed. These data are documented.

## 6.2 DISCUSSION OF DATA QUALITY

A summary of the precision, accuracy, and completeness achieved in the relevant measurements is listed in Table 6-1, along with the original goals for each type of measurement. In all cases, the completeness, accuracy, and precision of measurements met or exceeded the Quality Assurance objectives listed in the Quality Assurance Project Plan (QAPP) developed for the project.

Combustion gas flow was measured by a rotameter, combustion air flow measured by a venturi arrangement, and test liquid flows were measured by a rotameter. Initial calibrations of combustion gas flow rotameter and combustion air flow venturi are described in Appendices A1 and A2. Test liquid flow measuring rotameter was always inspected prior to use and its calibration was verified by a graduated cylinder/stop watch measurement

TABLE 6-1. DATA QUALITY SUMMARY

| Parameter (Method) | Completeness (%) | | Precision (%) | | Accuracy (%) | |
|---|---|---|---|---|---|---|
| | Planned | Actual | Planned | Actual | Planned | Actual |
| NO (Chemiluminescence) | a | >90 | a | 6.510 | 2.5 | 1.93 |
| CO (NDIR) | a | >90 | a | 3.004 | 5.0 | 0.14 |
| CO$_2$ (NDIR) | a | >90 | a | 1.13 | 5.0 | -0.10 |
| O$_2$ (Paramagnetic) | a | >90 | a | 0.587 | 2.5 | 0.43 |
| THC (Flame Ionization) | a | --- | a | 2.650 | 5.0 | -0.53 |
| Combustion Air Flows (b) | a | >90 | a | 0.047 (% RSD) | a | c |
| Combustion Gas Flows (b) | a | >90 | a | c | 5 | c |

a. Objectives were not defined in the QAPP
b. See Section 6.2 for explanation
c. Not done during the program

technique. Combustion gas flow field temperature was measured by a suction pyrometer. This suction pyrometer was calibrated as explained in Appendix A6. Combustion gas velocities were measured by a pitot probe as explained in Appendix A7. This pitot probe was inspected prior to use and found to be in good working order. Hence, factory calibration of this probe was assumed to be true.

An overall facility precision check was performed each test day by repeating an arbitrarily selected "baseline" data point at the end of a test sequence. If the NO and $O_2$ monitor readings were within 10 percent precision for the two baseline measurements, then overall facility operation was considered to be consistent.

Bourdon gauges measuring process pressures, and suction pyrometer measuring combustion gas temperatures were inspected periodically and found to be in good working order. Hence, accuracy of these elements was not checked.

In summary, the collected data are sufficient for the original intentions of the project.

# REFERENCES

1. Spalding, D.B. In: Proceedings of the Fourth Symposium (International) on Combustion, The Combustion Institute, 1952. p. 847.

2. Williams, A. Combust. Flame, (21)1, 1973.

3. Faeth, G.M. Combust. Sci. Tech., (21)123, 1977.

4. Law, C.K., Recent Advances in Droplet Vaporization and Combustion. Prog. Energy Combustion Science, (8):171-201, 1982.

5. Chiu, H.H., Ahluwalia, R.K., Koh, B., and Croke, E.J. Spray Group Combustion. Paper presented at the Sixteenth Aerospace Sciences Meeting, Huntsville, Alabama, January 1978.

6. Ayers, W.H., Boysan, F., and Swithenbank, J. Droplet Trajectories in Three Dimensional Gas Turbine Flow Fields. AFOSR-TR-81-0543, Air Force Report, September 1980.

7. Chigier, N., and McCreath, C.G. Combustion of Droplets in Sprays. Acta Astronautica, (1):687-710, 1974.

8. Kramlich, J.C., Seeker, W.R., and Samuelson, G.S. Influence of Atomization Quality on the Destruction of Hazardous Waste Compounds. Presented at the Twenty-first Symposium (International) on Combustion, The Combustion Institute, 1986.

9. Mulholland, J.A., Srivastava, R.K., and Ryan, J.V. The Role of Rogue Droplet Combustion in Hazardous Waste Incineration. In: Proceedings: Twelfth Annual Research Symposium on Incineration and Treatment of Hazardous Wastes, Cincinnati, Ohio, April 21-23, 1986, EPA-600/9-86-022 (NTIS PB87-119491), pp. 413-420.

10. Mulholland, J.A., Srivastava, R.K., Robinson, S.B, Lanier, W.S., and Wendt, J.O.L. Measurement and Prediction of Single Droplet Trajectories in a Swirled Combustion System. Poster presentation at the Twenty-first Symposium (International) on Combustion, Munich, West Germany, August 3-8, 1986.

11. Brown, R.A. Operation and Instruction Manual for EPA Versatile Furnace. Acurex Final Report No. 73-82, EPA Contract No. 68-02-0602, Sept. 2, 1973.

12. Leuckel, W. Swirl Intensities, Swirl Types and Energy Losses of Different Swirl Generating Devices. International Flame Research Foundation, Doc. No. G02/a16, 1968.

13. Beer, J.M., and Chigier, N.A. Combustion Aerodynamics. Applied Science Publishers Ltd., London, 1972.

14. Beer, J.M., and Chigier, N.A. Swirling Jet Flames from an Annular Burner. International Flame Research Foundation, Doc. No. K20/a91, 1963.

15. Seymour, R.J., and Boss, C.B. Design Modification for a Uniform Droplet Generator System. Applied Spectroscopy (37)4:375-379, 1983.

16. Sangiovanni, J.J., and Kesten, A.S. Effect of Droplet Interaction on Ignition in Mono-dispersed Droplet Streams. In: Proceedings of the Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1977. pp. 577-592.

17. Koshland, C.P., and Bowman, C.T. Combustion of Mono-disperse Droplet Clouds in a Reactive Environment. In: Proceedings of the Twentieth Symposium (International)on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1984. pp. 1799-1807.

18. Schlichting, H. Boundary Layer Theory. 4th Edition, McGraw Hill, New York, 1960, p. 16.

19. Lambiris, S., and Combs, L.P. Steady-State Combustion Measurements in a LOX-RP-1 Rocket Chamber and Related Spray Burning Analysis. Detonation and Two-Phase Flow, (6):283, 1962.

20. Dickerson, R.A., and Schuman, M.D. Rate of Aerodynamic Atomization of Droplets. Journal of Spacecraft and Rockets, (2):99-100, 1965.

21. Glauert, M.B., and Lighthill, M.J. The Axisymmetric Boundary Layer on a Long Thin Cylinder. In: Proceedings of the Royal Society of London, A, (230):188-203, 1955.

22. White, F.M. Applied Spectroscopy, (37)4:375-379, 1983.

23. Panton, R.L. Incompressible Flow. 1st Edition, John Wiley, New York, 1984. pp. 384-401.

24. Churchill, S.W. The Interpretation and Use of Rate Data: The Rate Concept. McGraw-Hill, New York, 1974. pp. 290-296.

25. Churchill, S.W., and Usagi, R. General Expression for the Correlation of Rates of Transfer and Other Phenomena. AIChE Journal, (18)6: 1121-1128, 1972.

26. Fornberg, B. A Numerical Study of Steady Viscous Flow Past a Circular Cylinder. J. Fluid Mech., (98)4:819-855, 1980.

27. Marquardt, D.L. An Algorithm for Least-Squares Estimation of Non-Linear Parameters. J. Soc. Indust. Appl. Math, (2):431-441, 1963.

28. Labowsky, M. Calculation of the Burning Rates of Interacting Fuel Droplets. Combustion Science and Technology, (22):217-226, 1980.

29. Sangiovanni, J.J., and Labowsky, M. Burning Times of Linear Fuel Droplet Sprays: A Comparison of Experiment and Theory. Combustion and Flame, (47):15-30, 1982.

30. Marberry, M., Ray, A.K., and Leung, K. Effect of Multiple Particle Interactions on Burning Droplets. Combustion and Flame, (57): 237-245, 1984.

31. Eisenklam, P., Arunachalam, S.A., and Weston, J.A. Evaporation Rates and Drag Resistance of Burning Drops. In: Proceedings of the Eleventh Symposium (International) on Combustion, The Combustion Institute, 1967, pp. 715-728.

32. Renz, W.E., and Marshall, W.R. Chem. Eng. Prog., (48):141-173, 1952.

33. Dukowicz, J.K. A Particle-Fluid Numerical Model for Liquid Sprays. Journal of Computational Physics, (35):229-253, 1980.

# APPENDIX A

# HARDWARE DETAILS

## A1: NATURAL GAS FLOWRATE CALIBRATION AND MEASUREMENT

House natural gas supply at 5 psi was tapped for supply to the droplet studies' furnace. The natural gas supply was metered by a Brooks Rotameter which was calibrated on 09/18/84. The calibration setup is shown in Figure A1 and the results of the calibration are tabulated in Table A1.

Table A1

Results of the Natural Gas Calibration

| Data Pt. | $P_1$ (psi) | Rotameter SCFM @ 5 psi | Actual* SCFM | $P_2$ (psi) | Dry Gas Meter GFM @ 5 psi | Actual* SCFM |
|---|---|---|---|---|---|---|
| 1 | 4.9 | 2.91 | 2.90 | 4.7 | 2.05 | 2.71 |
| 2 | 4.8 | 4.06 | 4.04 | 4.5 | 3.11 | 4.06 |
| 3 | 4.8 | 3.64 | 3.62 | 4.5 | 2.80 | 3.66 |
| 4 | 4.6 | 5.16 | 5.11 | 4.5 | 4.00 | 5.22 |

$$\text{*Actual SCFM} = \text{Rotameter Reading} \times \sqrt{\frac{14.7 + P_1}{14.7 + 5.0}}$$

$$\text{*Actual SCFM} = \text{Dry Gas Meter CFM (@ 5 psi)} \times \frac{14.7 + P_2}{14.7}$$

The calibration results show that there is very close agreement between the rotameter and dry gas meter readings; at about 3 scfm the difference between the two is less than 7 percent while at higher flowrates (>3.6 scfm) the difference is less than 2 percent. Thus keeping in view the accuracy of rotameter to be greater than that of dry gas meter, rotameter readings were used for gas measurement.

Note: 1 psi = 6.895 kPa

1 scfm = 0.0283 $m^3$/min

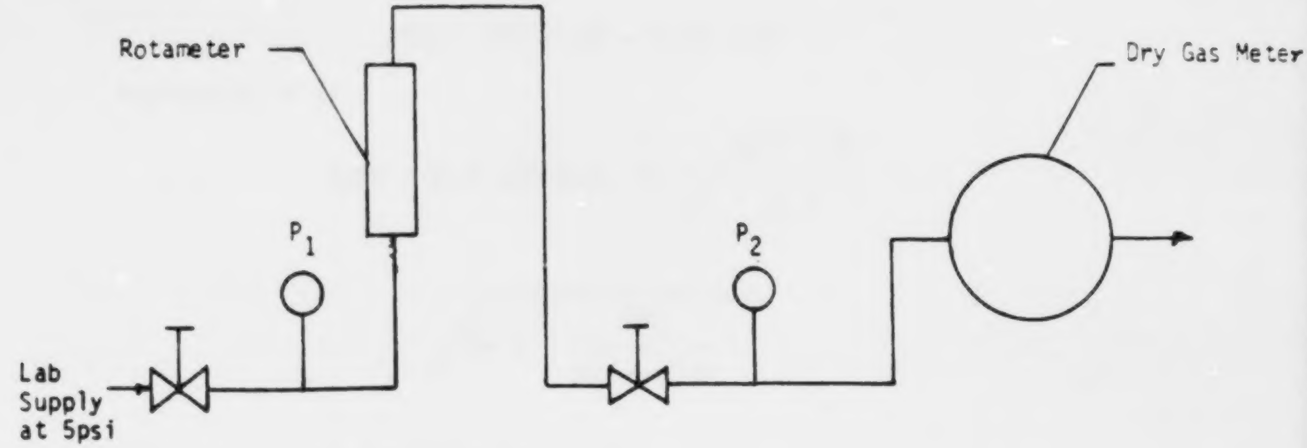

Rotameter
Dry Gas Meter
$P_1$
$P_2$
Lab Supply at 5psi

Figure A1. Natural Gas Calibration Setup

## A2: COMBUSTION AIR FLOWRATE CALIBRATION AND MEASUREMENT

The air for the droplet studies' furnace was supplied from a Worthington model 25RS100 monorotor air compressor (the specifications are shown in Figure A2).

The air supply setup is shown in Figure A3. The flow-measuring device -- venturi -- was calibrated against the $O_2$ monitor readings or excess air levels in the furnace at various air settings. A plot of $O_2$, $CO_2$ emissions versus excess air levels was developed using natural gas analysis and combustion calculations. This plot, shown in Figure A4, was used during air calibration to correlate $O_2$ emissions with various excess air levels or air settings. Finally, the results of the calibration are shown in Figures A5 and A6. Using the best-fit curve shown in Figure A5, the following formula could be derived for air flowrate:

$$\text{SCFM} = (37.6\sqrt{\Delta P} - 0.04)\, F_P F_T$$

neglecting -0.04,

$$\text{SCFM} = 37.6\sqrt{\Delta P}\, F_P F_T;\quad F_P = \sqrt{\frac{14.7 + P_1}{14.7}}$$

$$\sqrt{F_T = \frac{530}{460 + T(^\circ F)}}$$

$P_1$ vs. $\Delta P$ are obtained from Figure A6.

| | |
|---|---|
| Model Number | 25RS100 |
| Capacity @ 1750 rpm | |
| CFM @ 100 psig | 100 (689 kPa) |
| Operating Pressure | |
| Range, psig | 80-125 (551 kPa-861 kPa) |
| Factory Settings | |
| Modulating Control | |
| Full Capacity, psig | 102 (703 kPa) |
| 0 Capacity, psig | 110 (758 kPa) |
| Dual Control | |
| Cut-in, psig | 103 (710 kPa) |
| Cut-out, psig | 115 (793 kPa) |
| (Adjustable Pressure Switch) | |
| Ambient Temperature | |
| Limits, °F | 10-100 (260 K - 310 K) |
| Heat Regection to Room, Btu/min | 1322 (23 kW) |
| Oil Capacity, U.S. | |
| Gallons | 5 (0.02m$^3$) |
| Motor Horsepower | 25 (18.6 kW) |
| (Standard NEMA Open Dripproff Induction Type, 1800 rpm, 3 phase, 60 cycle, available for voltages of 200, 230/460 and 575.) | |
| Contro Circuit Transformer | |
| Voltage, AC | 115 |

Figure A2. Worthington compressor specifications.

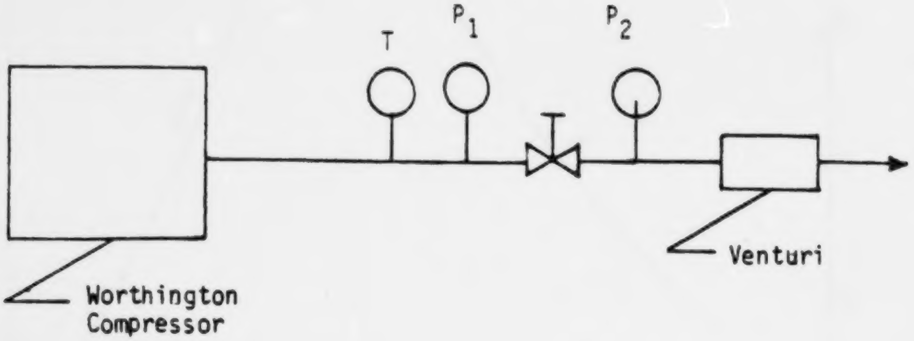

T
$P_1$
$P_2$
Worthington Compressor
Venturi

Figure A3. Combustion air calibration setup

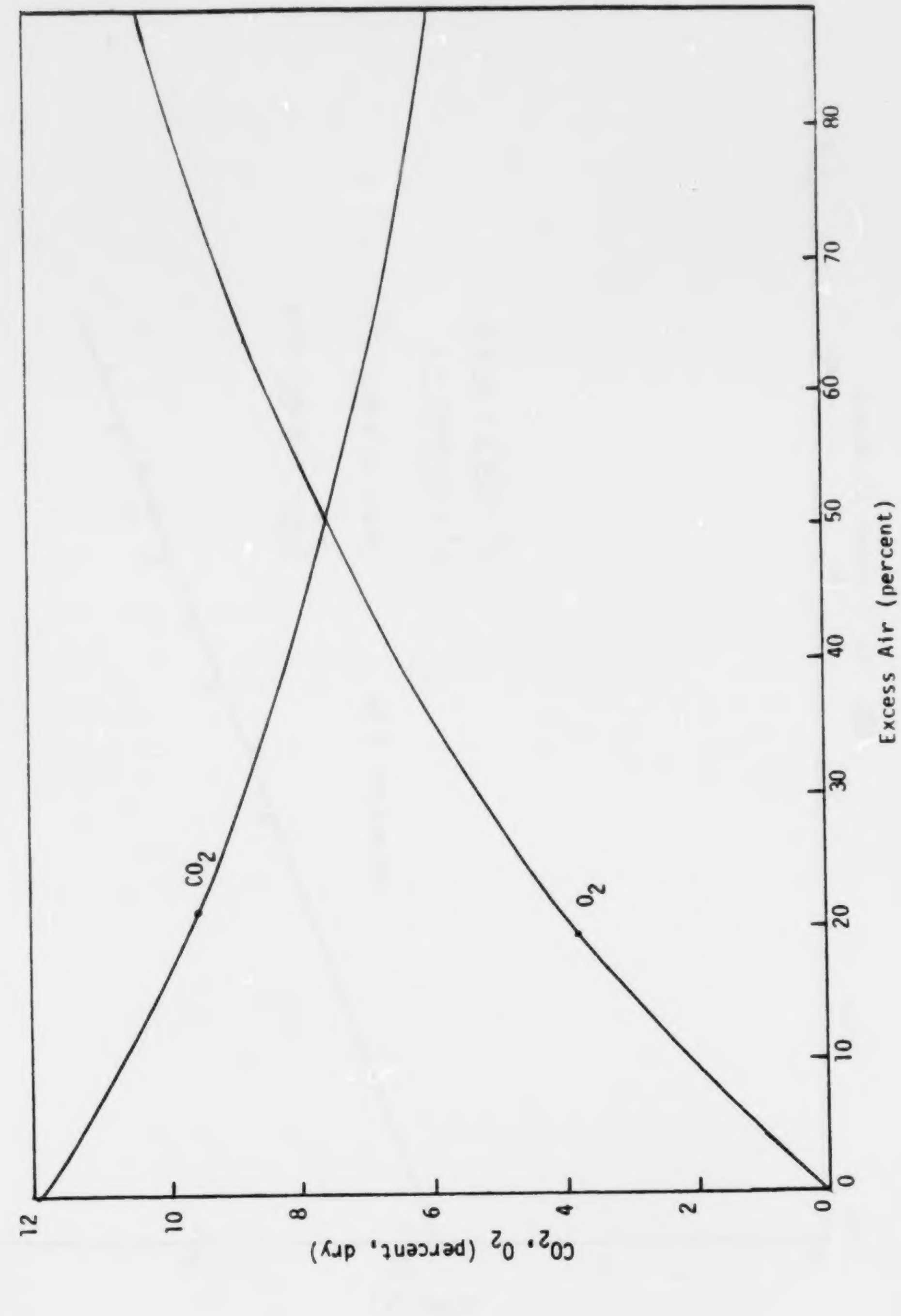


Figure A4. CO$_2$ and O$_2$ emissions from firing laboratory natural gas

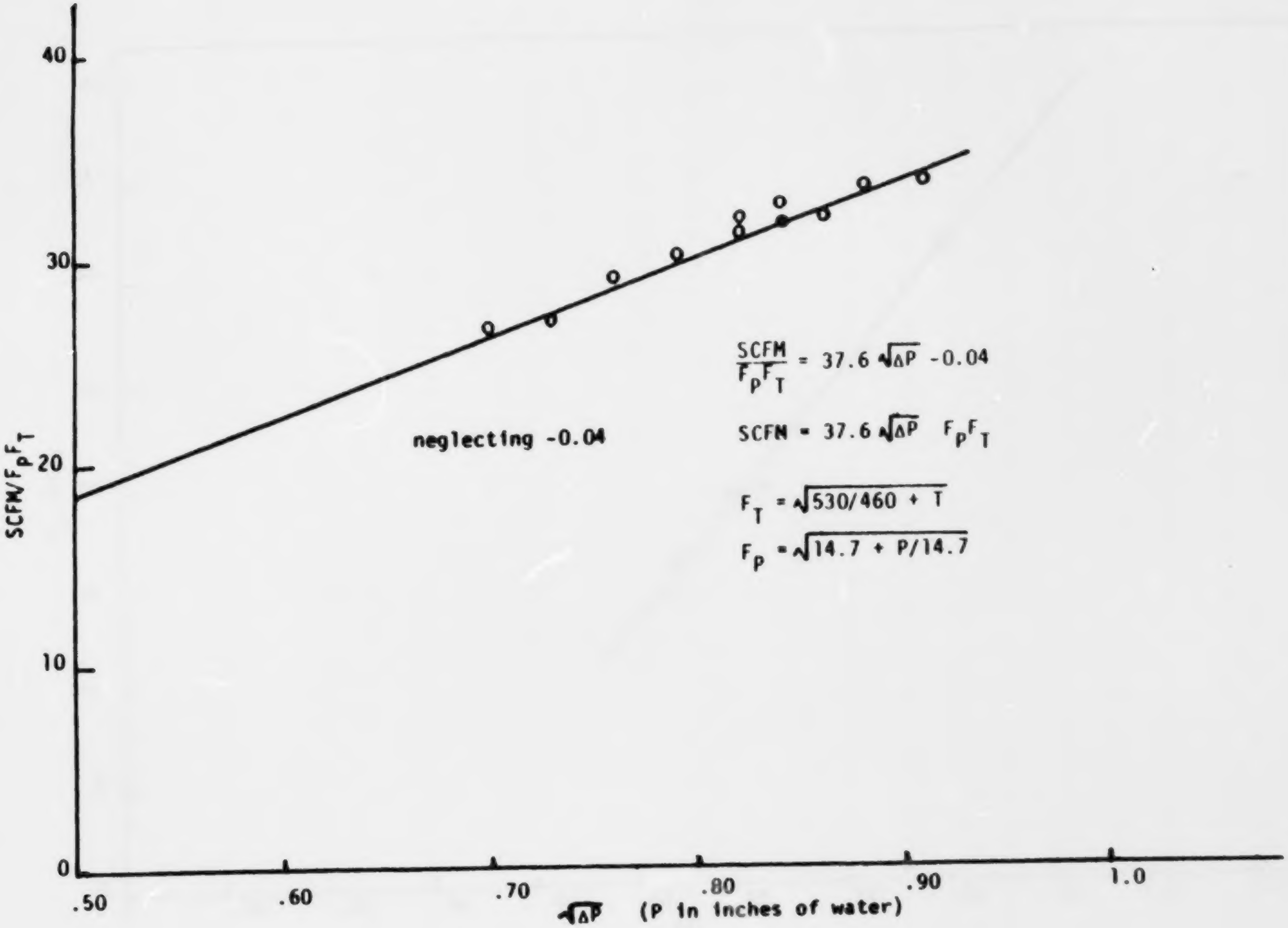


Figure A5. Combustion air venturi calibration, SCFM/$F_PF_T$ vs. $\sqrt{\Delta P}$

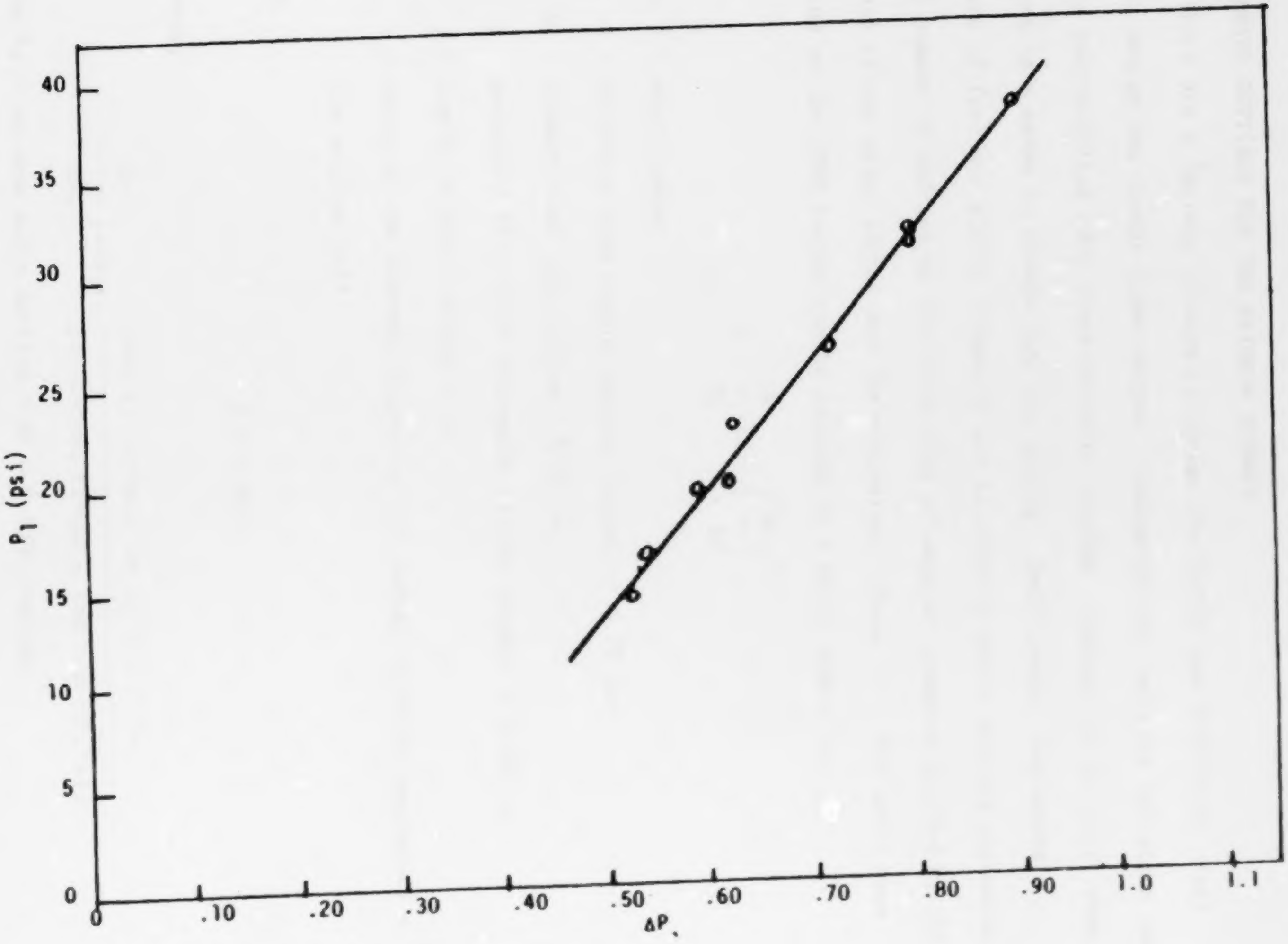


Figure A6. Combustion air venturi calibration, $P_1$ vs. $\Delta p$

## A3: SWIRL SETTINGS FOR THE RAINBOW FURNACE

There are a variety of ways to change the burner gas flowfield. Fuel nozzle design can change flame shapes. Combustion air velocity variation can change recirculating eddy characteristic lengths. Combustion air swirl vane setting is a means to change fuel-air mixing. Swirl number represents a measure of fuel/air mixing intensity and is often a useful scaling parameter. Swirl number is defined as the axial flux of angular momentum divided by the product of the axial thrust and the equivalent radius.(13) The swirl vane setting on the IFRF burner can be related to a swirl number by:

$$S = \frac{\sigma R}{ZB}\left[1 - \left(\frac{R_h}{R}\right)^2\right]$$

where S = swirl number

R = secondary flow radius (burner throat) = 0.78 in.

$R_h$ = primary fuel tube radius = 5/16 in.

B = secondary flow inlet dimension (block height) = 0.502 in.

Z = number of swirl blocks = 12

$\sigma$ = ratio of the average tangential and radial velocity components at the swirler exit

Thus,

$$S = 0.652\,\sigma$$

however,

$$= \frac{2\pi}{Z\varepsilon_m}(\sin\alpha)\frac{(\cos\alpha)\,[1+\tan\alpha\,\tan(\varepsilon/2)]\,(\varepsilon/\varepsilon_m)}{[1-[1-\cos\alpha\,(1+\tan\alpha\,\tan\varepsilon/2)](\varepsilon/\varepsilon_m)]}$$

where $\varepsilon_m$ = maximum angle setting = 8° = 0.1396 radians

$\alpha$ = block angle = 50°

$\varepsilon$ = actual angle setting (variable: 0 to 8)

quarl divergence = 30°

quarl length = 2.25 in.

Therefore

$$S = \frac{1.204\,[1+1.192\tan(\varepsilon/2)]\,(\varepsilon/8)}{1-[1-0.643(1+1.192\tan(\varepsilon/2))](\varepsilon/8)}$$

Using the above formula, $\varepsilon$ and S can be tabulated as shown below:

| $\varepsilon$ (Angle Settings on IFRF Burner) | S (Swirl Number) |
|---|---|
| 0 | 0 |
| 1 | 0.159 |
| 2 | 0.336 |
| 3 | 0.533 |
| 4 | 0.751 |
| 5 | 0.993 |
| 6 | 1.259 |
| 7 | 1.552 |
| 8 | 1.870 |

A plot of IFRF angle settings vs. swirl number is shown in Figure A7.

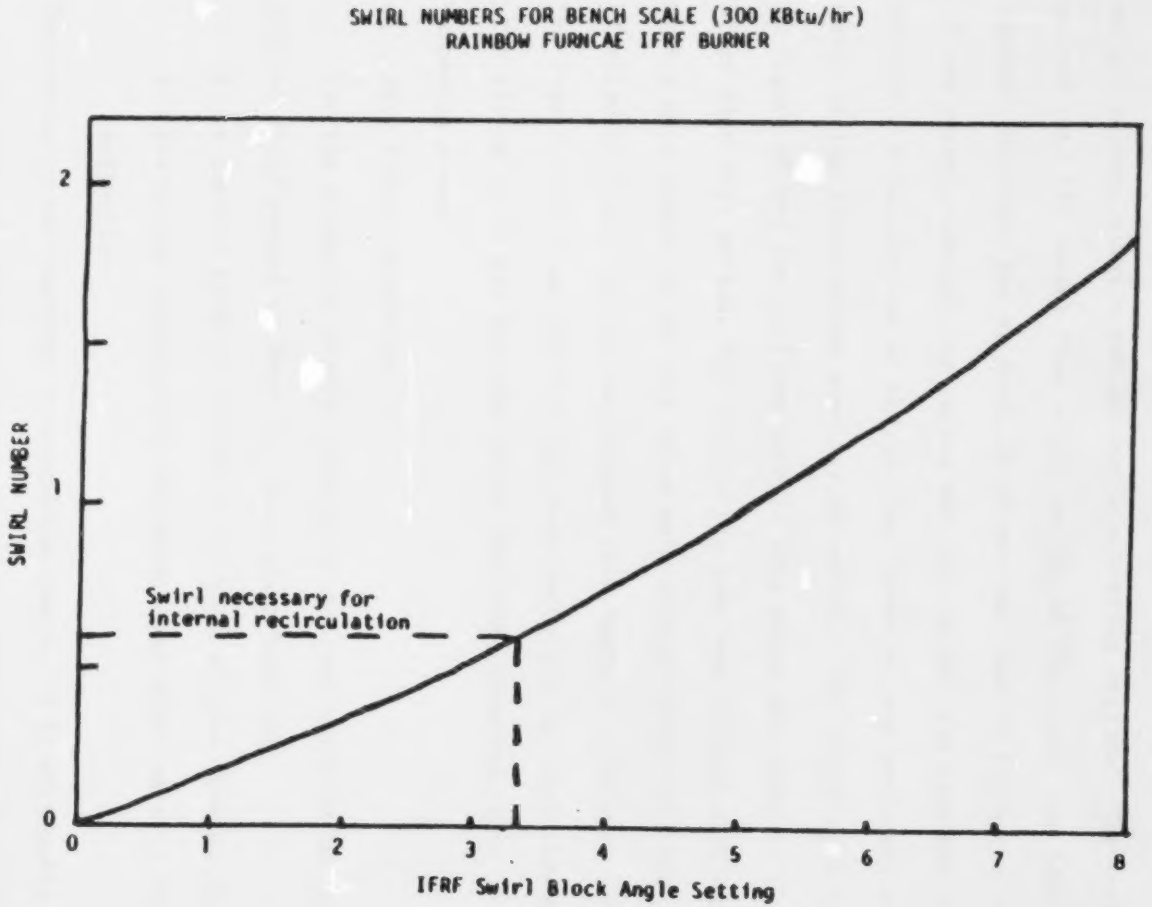


Figure A7. IFRF block angle settings vs. swirl number

## A4: LIQUID FEED SYSTEM

This system consisted of a pressure vessel rated to 200 psi at 450°F, an in-line rotameter for flow measurement, pressure and temperature gauges, on/off valves, plastic tubing, and a vibrating orifice. The test liquid was poured into the vessel from a port on top of the vessel and then the port was capped. Nitrogen gas at about 25-30 psi was used to force the test liquid out of the vessel, through the valves and the tubing, and into the vibrating orifice. A calibration of the in-line rotameter was performed with each new batch of the fluid volume over a time period. The liquid feed system is shown in Figure A8 and the orifices used in this study are shown in Figure A9. After each test period, the orifice (in use) was cleaned with heptane. Liquid spills were soaked up in rags which were appropriately disposed and the area affected by liquid spills was cleaned with heptane. Periodic leak checks of the liquid flow lines and fittings were performed by pressurizing the system with air up to 15 psi and then using the leak-detection fluid (Snoop) over suspected areas.

## A5: TEST LIQUID SELECTION

For the scheme of droplet generation process selected for this study the droplet fluid needed to have two important properties:

1. A certain band of viscosity for good droplet forming characteristics
2. Electrical conductivity characterizing electrostatic charging and deflection

The viscosity was measured in a relative sense. A 25 ml pipette was filled with the desired liquid and then allowed to drain vertically. The time of draining characterized the viscosity of the fluid. Once a particular batch of fluid was found to form good droplets, subsequent batches of fluid were matched to this standardized viscosity.

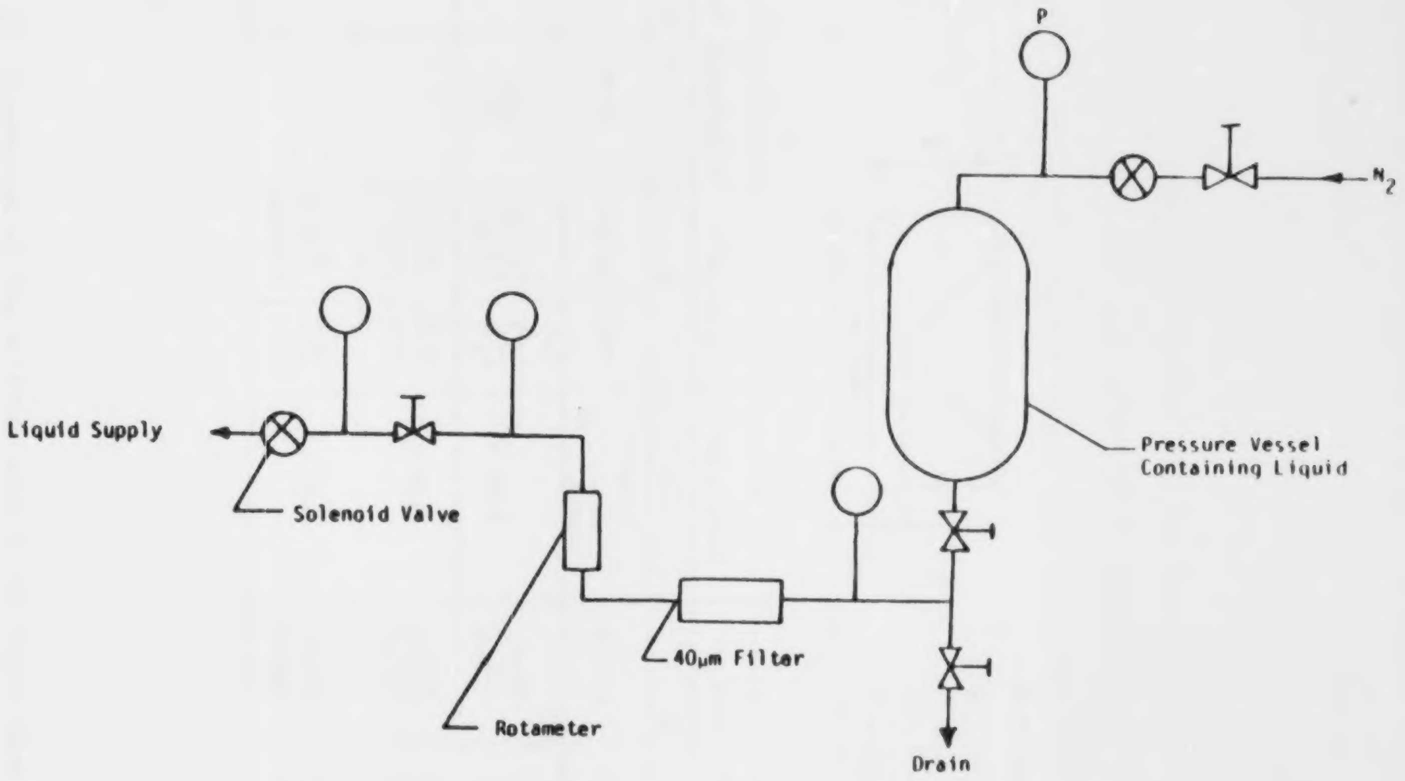
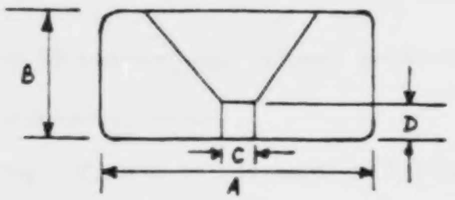

P
N2
Liquid Supply
Solenoid Valve
Rotameter
40μm Filter
Pressure Vessel
Containing Liquid
Drain

Figure A8. A schematic of the liquid feed system



A - Outside Diameter

B - Thickness

C - Orifice Diameter

D - Orifice Length

| OUTSIDE DIAMETER | | THICKNESS | | HOLE SIZE | ORIFICE LENGTH | |
|---|---|---|---|---|---|---|
| A | | B | | C | D | |
| INCHES | MM | INCHES | MM | INCHES TOL. $^{+0.0002''}_{-0.0000''}$ | INCHES | MM |
| 0.0646<br>0.0650 | 1.64<br>1.65 | 0.0237<br>0.0256 | 0.60<br>0.65 | 0.004 | 0.0059<br>0.0119 | 0.15<br>0.30 |
| | | 0.0276<br>0.0295 | 0.70<br>0.75 | 0.006 | 0.0099<br>0.0158 | 0.25<br>0.40 |
| | | 0.0315<br>0.0335 | 0.80<br>0.85 | 0.008 | 0.0130<br>0.0180 | 0.33<br>0.46 |

Figure A9. Dimensions of the orifices used in the liquid feed system

The electrical conductivity was measured with an immersible electrode conductivity meter. It was found through experimentation that a minimum conductivity of 4 mho's was required to impart a significant charge on a single droplet.

The two fluids calibrating the above two properties were found to be:

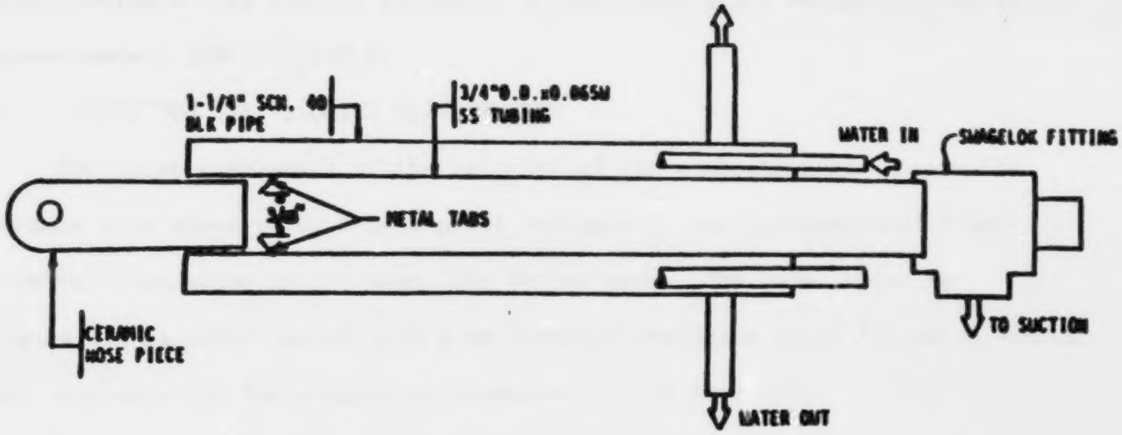
- A mixture of 80 percent (by volume) Shell fluid additive ASA-3, comprised mostly of xylene and 20 percent (by volume) distillate fuel oil
- A mixture of 75 percent (by volume) water ($H_2O$) and 25 percent (by volume) glycerine ($C_3H_8O_3$)

The first fluid being inflammable was used in combustion atomization studies while for the cold flow tests both fluids were used. The properties of the test liquids are appended herein (see end of Appendix A).

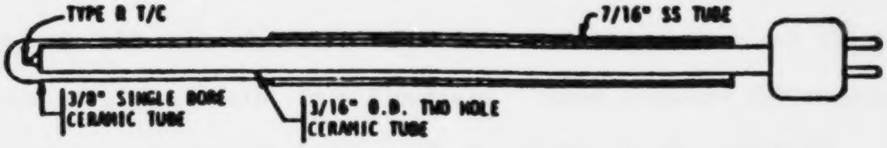
## A6: TEMPERATURE MEASUREMENTS USING A SUCTION PYROMETER

The suction pyrometer designed for in-flame temperature measurement in the furnace was a 1.0 m (3.3 ft) long probe for radial transverses. The basic design of the suction pyrometer is shown in Figure A10. Platinum and platinum/13 percent rhodium 10 mil (0.254 mm diameter) thermocouple wire is fed through a two-hole alumina tube and welded to form an R-type thermocouple junction. The thermocouple is slipped inside a 0.635 cm (0.25 in.) diameter alumina tube with a closed end for radiation shielding. To complete the suction pyrometer, the shielded R-type thermocouple is slipped into the water-cooled probe assembly. The thermocouple tip extends 15 cm (6 in.) past the end of the water-cooled probe, inside a close-end alumina nosepiece with a 0.635 cm (0.25 in.) hole near its tip (see Figure A10).

Suction for the pyrometer is provided by a carbon vane pump; the flowrate is monitored by a dry gas meter. The pump and the meter are protected from moisture by an EPA Method 5 condensation train consisting of two impingers and


1-1/4" SCH. 40
BLK PIPE
3/4"O.D.x0.065W
SS TUBING
WATER IN
SWAGELOK FITTING
3/8"
METAL TABS
TO SUCTION
CERAMIC
NOSE PIECE
WATER OUT

PART B- WATER COOLED PROBE ASSEMBLY


TYPE R T/C
7/16" SS TUBE
3/8" SINGLE BORE
CERAMIC TUBE
3/16" O.D. TWO HOLE
CERAMIC TUBE

PART A- SHIELDED THERMOCOUPLE

Figure A10. Suction pyrometer design

a silica gel trap in an ice bath. Thermocouple output is read by an Omega Model 2166A digital thermometer.

When in operation, hot combustion gases are pulled at a high velocity through the nosepiece port and down the annulus between the nosepiece and the shielded thermocouple. As the gas flowrate across the shielded thermocouple increases, convective heat transfer to the thermocouple tip predominates radiative transfer to the cold boiler walls, and the actual gas temperature is approached. Figure A11 shows that at flow rates in excess of 110 l/min the actual gas temperature is approached by the suction pyrometer. The construction of the suction pyrometer allows temperature measurement up to approximately 2000 K (3140°F).

## A7: COMBUSTION GAS VELOCITY MEASUREMENTS

The three components of the velocity of the combustion gas inside the furnace were measured by 5-hole pitot designed by the International Flame Research Foundation in IJniuden, The Netherlands. The probe shown in Figure A12 is water cooled with 8 mm uncooled stainless steel tip which allows any soot entering the stagnation pressure port to burn off.

### The Use of the 5-Hole Pitot Probe

The measurement of 5 pressure differentials across the holes on the probe's tip allow the determination of the velocity vector and the static pressure at a given point in a flowfield. These pressure differentials needed to be measured are $P_0-P_{atm}$, $P_1-P_3$, $P_2-P_4$, $P_0-P_3$, and $P_0-P_4$.

The velocity vector is defined in terms of angles $\psi,\delta$, and magnitude V. The angles $\psi$ and $\delta$ are defined as spherical coordinates shown in Figure A13. $\psi$ is the "geographic latitude," i.e., the angle between the velocity vector and the axis through the probe head; $\delta$ is the "geographic longitude," i.e., the angle between the plans head axis/velocity vector and head axis/line 1-3. The evaluation of velocity (magnitude V, direction $\psi,\delta$) and the static

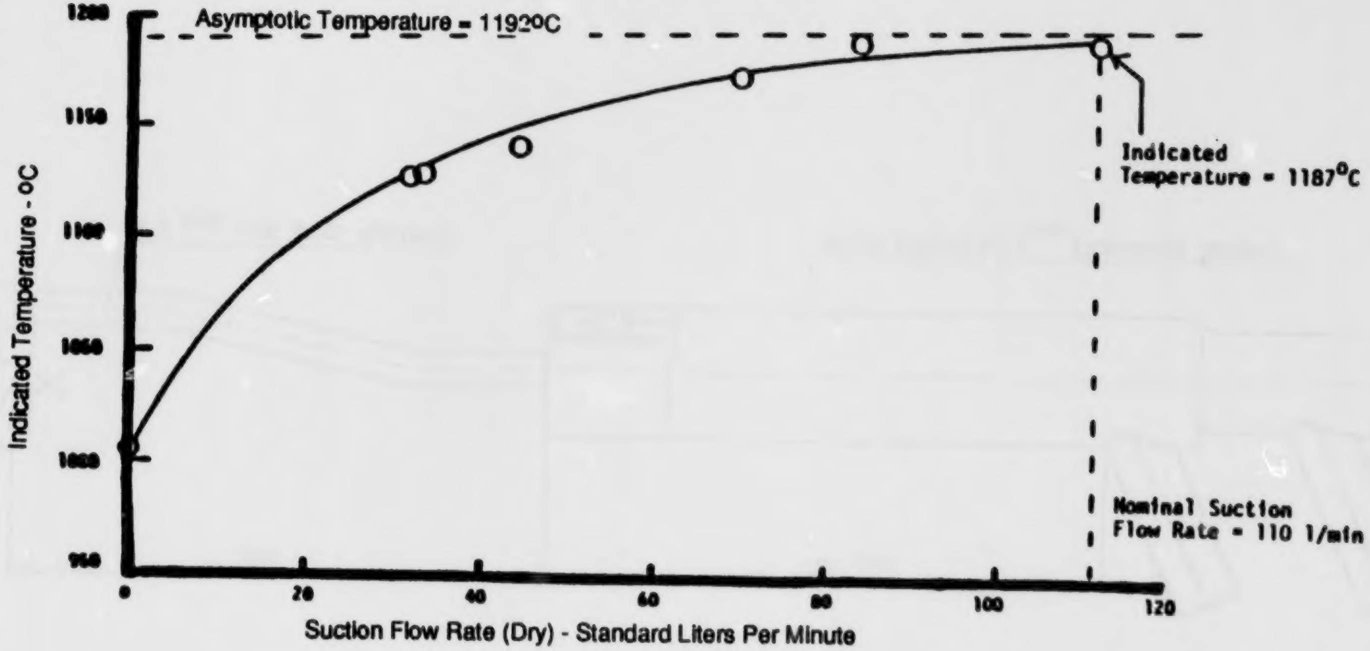


Figure A11. Suction pyrometer calibration curve

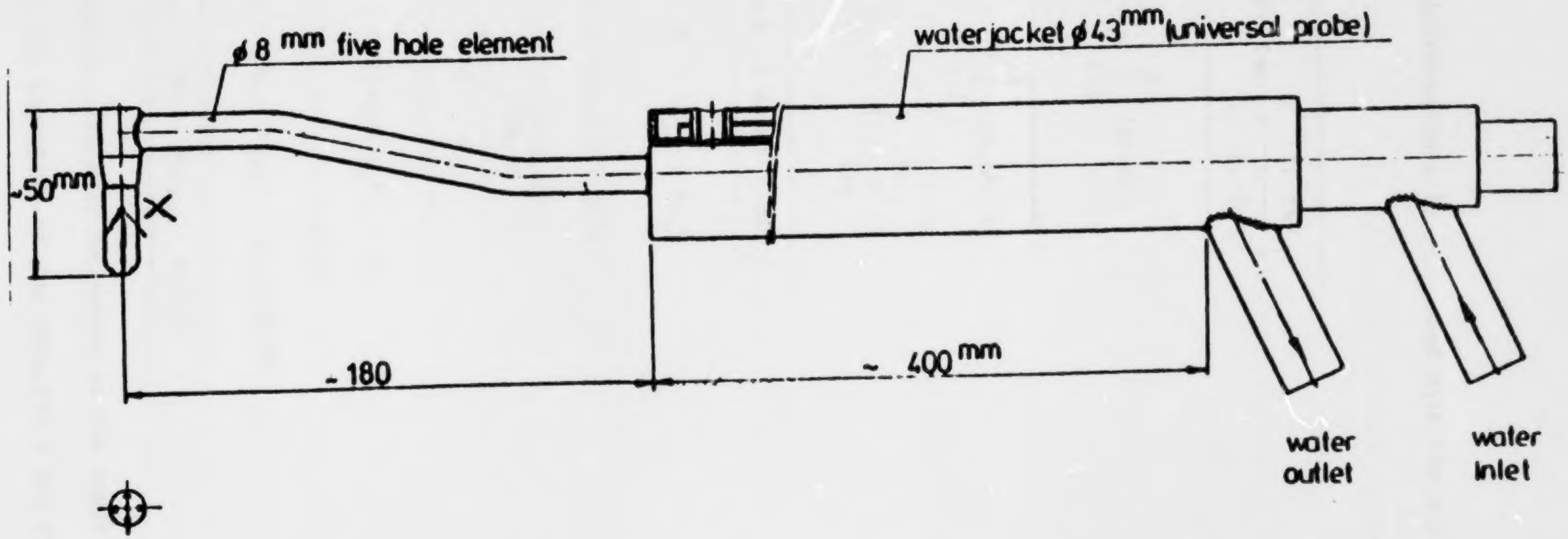

ø 8 mm five hole element
waterjacket ø 43 mm (universal probe)
~50 mm
X
~180
~ 400 mm
water outlet
water inlet

Figure A12. Five hole pitot probe

pressure from measured pressure differentials is performed with the aid of the equations:

$$\boxed{\delta = \arctan\left(-\frac{(P_2-P_4)}{(P_1-P_3)}\right)}$$

$$P_T = \sum_{i=1}^{4} (P_0-P_i)$$

$$P_R = \sqrt{\sum_{i-1}^{4} (P_0-P_i)^2}$$

$$k_\psi = 1 - \frac{P_T}{2P_R}$$

$$\boxed{\psi = A_1 k + A_3 k_\psi^3 + A_5 k_\psi^5}$$

$$k_v = B_0 + B_2\psi^2 + B_4\psi^4$$

$$P_{dyn} = 1/2\, \rho V^2 = k_v P_R$$

$$\boxed{V = \sqrt{\frac{2k_v P_R}{\rho}}}$$

$$k_p = 1 + C[\exp(-D\psi^2) - 1]$$

$$P_0 - P_{st} = k_p \cdot 1/2\rho V^2$$

$$P_{st} - P_{atm} = (P_0 - P_{atm}) - k_p\, 1/2\rho V^2$$

$$\boxed{P_{st} - P_{atm} = (P_0 - P_{atm}) - k_p k_v P_R}$$

**The coefficients $k_\psi$, $k_v$, and $k_p$ are only dependent on the angle $\psi$ and only very slightly dependent on the magnitude of the velocity V and the angle $\delta$.**

$A_1$, $A_3$, $A_5$, $B_0$, $B_2$, $B_4$, C and D are constants, belonging to a specific instrument and are determined from the calibration. During the calibration, the pressure differentials are measured at given angles $\Psi$, $\delta$, and for known magnitude of velocity. For the instrument used, the constants were:

$$A_1 = 38.525804$$

$$A_3 = 29.7702999$$

$$A_5 = -11.3708818$$

$$B_0 = 0.698577988$$

$$B_2 = -6.68787948E-05$$

$$B_4 = 1.76019925E-08$$

$$C = 3.67186577$$

$$D = 1.7589929E-04$$

Now, once V, $\Psi$ and $\delta$ are known, the 3 components of the velocity can be calculated by:

$$V_x = V \cos \Psi$$

$$V_y = V \sin \Psi \cos \delta$$

$$V_z = V \sin \Psi \sin \delta$$

from the geometry shown in Figure A13.

For use in this program, the probe was bent by 12° (Figure A14) so that the probe tip was in line with the probe axis. This was done to ensure that the velocity field point being sampled was aligned with the probe axis and thereby to the sampling port on the furnace through which the probe was being inserted. Thereafter two axis transformations were used to correlate the bent probe axis to the combustor axis. These transformations are shown in Figures A14 and A15. The probe was connected to Setra Systems Inc. Model 239 pressure transducers and a compressed air purging system. The output of the pressure transducers was sent to an Apple computer. The schematic of the velocity measurement setup is shown in Figure A16. The equations relating the

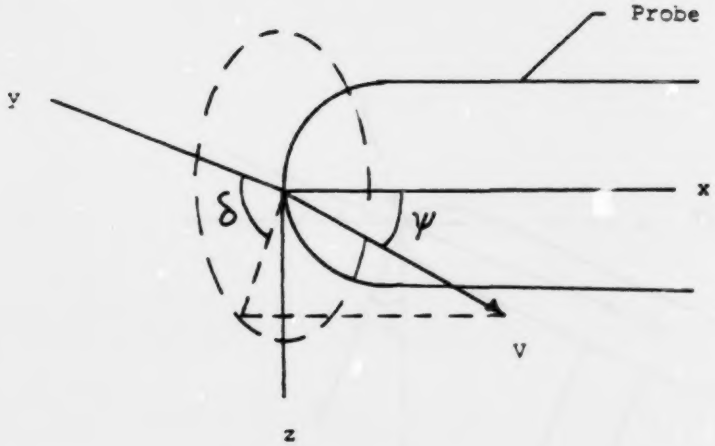
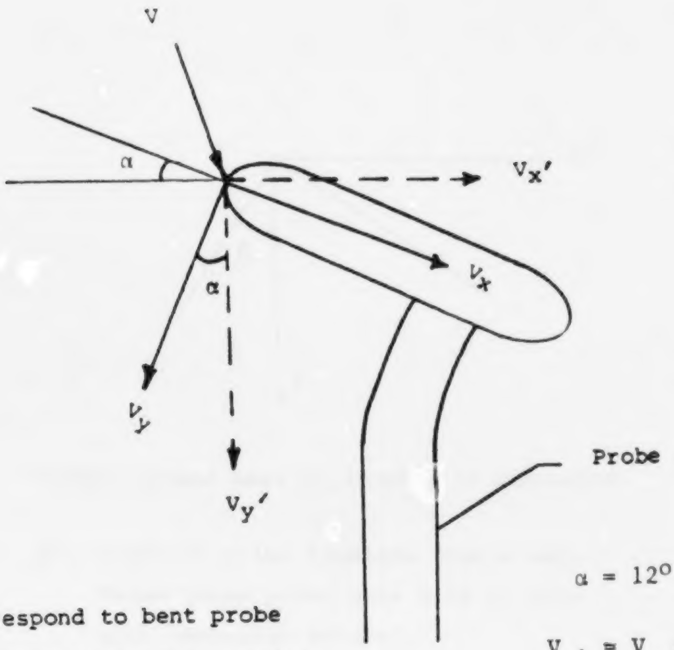

Probe
y
x
δ
ψ
V
z

Figure A13. Depiction of combustion gas velocity in a spherical coordinate system



Unprimed axes correspond to bent probe
Primed axes correspond to straight probe

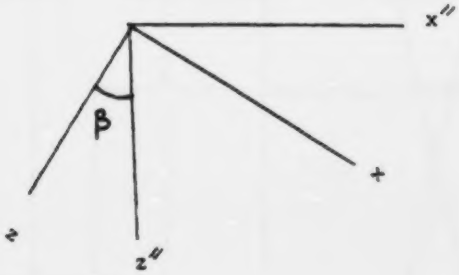
$\alpha = 12^\circ$

$$V_{x'} = V_x \cos \alpha - V_y \sin \alpha$$

$$V_{y'} = V_x \sin \alpha + V_y \cos \alpha$$

$$V_{z'} = V_z$$

Figure A14. Transformation relating bent probe axes to straight probe axes



Double primed axes correspond to combustor

β = angle of probe rotation from a zero
datum (when probe axis x is in line
with combustor axis x).

Figure A15. Transformation relating straight probe axes to combustor axes

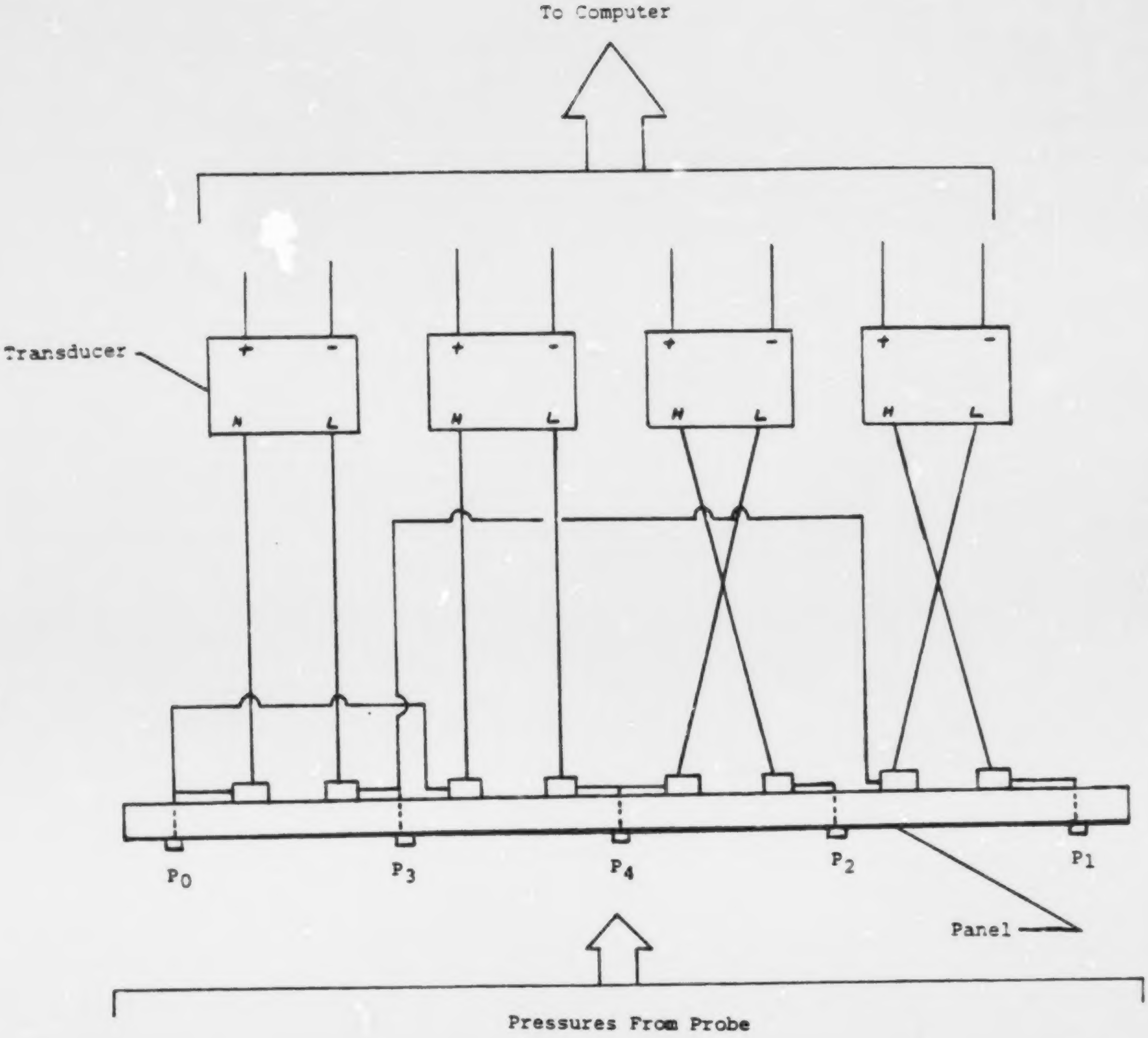

To Computer
Transducer
+
-
H
L
$P_0$
$P_3$
$P_4$
$P_2$
$P_1$
Panel
Pressures From Probe

Figure A16. A schematic of velocity measurement setup

measured pressure differentials and combustion gas temperature to combustion gas velocity at any point in the flowfield and the axis transformations relating the bent probe axis to combustor axis are incorporated into a computer program which then calculates combustion gas velocity at the spatial point being sampled. This computer program is appended at the end of this section.

The velocity measurement system was then tested for repeatability and consistency. These results are tabulated in Table A1. Based on the results given in Table A1, the following procedure was adopted for velocity measurement:

1) Sample at the axial ports 2", 10", 18", 26", and 34" on the combustor
2) At axial ports 2" and 10", sample at the radial locations -4", -3", -2", -1", 0", 1", 2", 3", 4", 5", 6", 7", and 8"
3) At axial ports 18", 26", and 34", sample at the radial locations 0", 4", and 8"
4) At any radial and axial locations' combination, rotate probe through angle $\beta$ = 0°, 40°, 80°, 120°, 160°, 200°, 240°, 280°, 320°, and 360°, and sample at each angular position
5) At any probe location (axial/radial/angular),
    a) Run 10 zeroes to check the calibration of pressure transducers
    b) Run 25 sample readings with velocity
    c) Purge and run 10 zeroes
    d) Run 25 sample readings with velocity
    e) If b) and d) agree, go to next point. If b) and d) disagree, repeat above procedure.

TABLE A1.

| Pt | Axial | Radial | Geo. Angle | Lat. | V | $V_x$ | $V_y$ | $V_z$ | Sample Size N |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 0 | 220 | 26.351 | 41.0158 | -20.0393 | 15.8193 | -26.1028 | 25 |
| 2 | 2 | 0 | 220 | 21.0885 | 37.009 | -24.9181 | 17.709 | -18.8987 | 25 |
| 3 | 2 | 0 | 220 | 15.9683 | 40.3539 | -27.9032 | 17.5747 | -22.2366 | 25 |
| 4 | 2 | 0 | 220 | 22.773 | 38.3566 | -23.8151 | 14.472 | -22.0956 | 25 |
| 5 | 2 | 0 | 220 | 18.1986 | 39.9081 | -28.9625 | 17.4078 | -19.7089 | 25 |
| 6 | 2 | 0 | 220 | 14.1161 | 32.093 | -20.0026 | 20.4445 | -5.2233* | 25 |
| 7 | 2 | 0 | 220 | 18.996 | 41.1614 | -30.231 | 18.3731 | -19.4792 | 25 |
| 8 | 2 | 0 | 220 | 21.4031 | 40.6751 | -25.7226 | 20.9214 | -22.328 | 25 |
| 9 | 2 | 0 | 220 | 18.5054 | 45.4421 | -40.6585 | 7.9198 | -17.1915* | 25 |
| 10 | 2 | 0 | 220 | 24.4375 | 10.2382 | -32.2612 | 18.4666 | -13.3619 | 25 |
| 1 | 2 | 0 | 220 | 36.0807 | 34.4275 | -28.5278 | 14.1577 | -4.9777 | 25 |
| 2 | 2 | 0 | 220 | 30.493 | 35.072 | -26.8626 | 16.3937 | -10.1171 | 25 |
| 3 | 2 | 0 | 220 | 30.4341 | 35.2901 | -26.1213 | 19.7742 | -10.4296 | 25 |
| 4 | 2 | 0 | 220 | 30.9684 | 34.4104 | -26.5196 | 18.3273 | -8.9669 | 25 |
| 5 | 2 | 0 | 220 | 27.1249 | 38.6461 | -28.7122 | 20.7541 | -13.599 | 25 |
| 6 | 34 | 0 | 0 | 59.7172 | 18.6879 | 8.817 | 0.6323 | 1.4456 | 25 |
| 7 | 34 | 0 | 0 | 62.6901 | 17.3998 | 8.1101 | -3.0384 | 0.5517 | 25 |
| 8 | 32 | 0 | 0 | 56.7454 | 19.1631 | 9.9147 | -0.76 | 1.653 | 25 |
| 9 | 2 | 0 | 220 | 30.1316 | 36.345 | -26.2799 | 20.024 | -11.2467 | 25 |

Remarks: 1) Before taking Pts. 6-10 (11/6) and 4-5 (11/7), the probe position was distubed and restored.
2) Pts. marked * seem to be inconsistent.

Conclusions:
1) Pts. 1,2,3,4,5,7,8,10 (11/6) and Pts. 1,2,3,4,5,9 (11/7) --> day-to-day repeatability
2) Pts. 1-5 (11/6); 7,8,10 (11/6); 1,2,3 (11/7); and 4,5 (11/7) --> small changes in probe positioning do not affect data significantly
3) All above points except those marked with * exhibit repeatability for multiple readings.
4) Pts. 1-5 and 9 (11/7) --> repeatability at the end of the day.
5) Pt. 6-8 (11/7) exhibit a sort of plugged flow--consistent
6) Sample size 25 seems to be alright.

## A8: CONTINUOUS EMISSIONS MONITORING SYSTEM (CEMS)

### Stack Gaseous Species Measurement

A schematic of the continuous emissions monitoring system (CEMS) is shown in Figure A17. The combustion gas sample at about 1 lit/min is extracted through a stainless steel probe inserted across the stack cross-section. Transported in stainless and teflon tubing, the sample gas passes through a refrigeration type condenser Hankison Series E as well as a Dryrite™ cannister for further drying before going to individual analyzers for oxygen, carbon dioxide, carbon monoxide and $NO_x$. Total hydrocarbons are analyzed separately via a separate heated sample line in order to prevent condensation of the heavier hydrocarbons. Table B1 lists the gaseous emission monitor specifications while Tables B2 and B3 list QA/QC procedures for this project.

### In-Flame Gaseous Species Measurement

In-flame gas combustion samples are drawn with a 1.0 m sampling probe shown in Figure A18. The probe made of stainless steel and of a water-cooled design is inserted from the side ports on the furnace. Combustion gas from in-flame zones is extracted through the stainless steel probe, transported in stainless and teflon tubing through a dryrite cannister in line and onto the CEMS described above. Sample flow rate was about 1 lit/min.

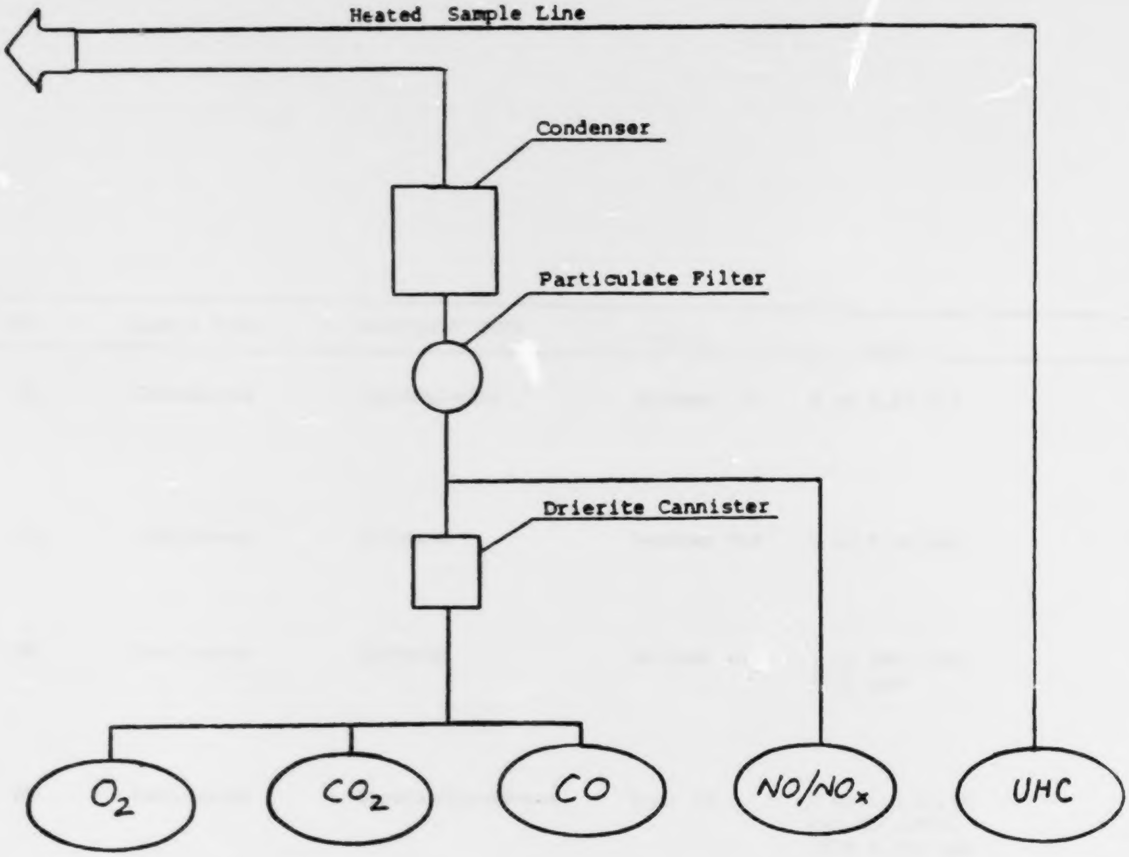

Heated Sample Line
Condenser
Particulate Filter
Drierite Cannister
$O_2$
$CO_2$
CO
$NO/NO_x$
UHC

Figure A17. A schematic of continuous emissions monitoring system (CEMS)

Table B1

| GAS | SAMPLE TYPE | INSTRUMENT TYPE | MODEL | RANGE |
|---|---|---|---|---|
| $O_2$ | Continuous | Paramagnetic | Beckman F3 | 0 to 5,10,25% |
| $CO_2$ | Continuous | Infrared | Beckman 864 | 0 to 5,10,20% |
| CO | Continuous | Infrared | Beckman 865 | 0 to 500,1000, 2000 ppm |
| NO | Continuous | Chemiluminescence | Teco 10 | 0 to 2.5,10,25 100,250,1000, 2500,10000 ppm |
| THC | Continuous | Flame Ionization | Beckman 402 | 0 to 10,50,100, 500,1000,5000, 10000,50000 ppm |

TABLE B2

Quality Assurance Objectives for Species Measurements

| Measured Parameter (Method) | Calibration Method | Calibration Frequency | Accuracy (percent of calibration standard) |
|---|---|---|---|
| CO (Infrared) | Cal. Gas | Twice each test day | 5 |
| $CO_2$ (Infrared) | Cal. Gas | Twice each test day | 5[a] |
| $O_2$ (Paramagnetic) | Cal. Gas | Twice each test day | 2.5[a] |
| NO (Chemiluminescence) | Cal. Gas | Twice each test day | 2.5[a] |
| THC (Flame Ionization) | Cal. Gas | Twice each test day | 5 |

[a] Gaseous Continuous Emission Monitoring Systems--Performance specification guidelines for $SO_2$, $NO_x$, $CO_2$, $O_2$, and TRS. EPA-450/3-82-026, October 1982.

## TABLE B3

### Calibration Requirements for Critical Control Instrumentation

| Measured Parameter (Method) | Calibration Method | Calibration Frequency | Accuracy (percent of calibration standard) |
|---|---|---|---|
| Process Temperature (Bi-metal thermometer) (Thermocouple) | $H_2O$ phase change | Annually | 2 |
| Process Pressures (Bourden-tube Gauge) | $H_2O$ U-tube manameter | Annually | 2 |
| Temperature (Suction Pyrometer) | Temperature versus Flow Curve | Prior to Use | 5 |
| Velocity (Pitot Probe) | Mass Flow Calibration | Each Boiler Traverse | 10 |
| Gas Flows (Rotameter) | Dry Gas Meter/ Stopwatch | Annually | 5 |
| Liquid Flows (Rotameter) | Graduated Cylinder/ Stopwatch | Each Liquid Refill | 5 |
| Air Flow (Venturi) | Measuring excess $CO_2$ | Annually | 10 |

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## prepared for

Acurex Corporation
Case No. 19194

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## TECHNICAL REPORT

19 May 1987

Page 1 of 3

**CLIENT:**

Acurex Corporation
P.O. Box 13109
Research Triangle Park
North Carolina 27709

Attention: Mr. Ravi K. Srivastava

**CASE NO:** 19194

**REFERENCE:** Purchase Order No. ER 14518Z

**PROJECT DESCRIPTION:**

Analysis of liquid sample by Density measurement, ash content, Thermogravimetric Analysis and Gas Chromatography - Mass Spectroscopy.

**SAMPLE IDENTIFICATION:**

1 of 1 - One bottle of dark colored liquid.

The above sample was received on 27 April 1987.

**METHOD OF TEST:**

Density was determined by the Pycnometer Method.

Ash content was determined by the Bunsen Burner Technique.

Thermogravimetric Analysis were performed on DuPont 950 Analyzer from room temperature to 500°C at 10°/min. under nitrogen atmosphere.

Extrel 400-2 Mass Spectrometer coupled to Varian 3400 Gas Chromatograph was used in the GC-MS Analysis.

**RESULTS:**

- The density and ash content of the liquid sample were as follows:

| | |
|---|---|
| Density | 0.8133 g/cm$^3$ |
| Ash Content | 1.32% |

This report is rendered upon all of the following conditions: Skinner & Sherman Laboratories, Inc. retains ownership of this report until associated submitted invoice is satisfied. Expert witness services shall be available in conjunction with this report only if prior notification of this potential requirement was made and accepted, before the analysis. This report is not to be reproduced wholly or in part without special permission in writing. Total liability is limited to the invoice amount. Skinner & Sherman, Inc., Skinner & Sherman Technology, Inc., and/or New England Laboratories name and/or logos may not be used in conjunction with the contents of this report in any advertising media. The results listed refer only to tested samples and applicable parameters. Product endorsement is neither inferred nor implied. Skinner & Sherman Laboratories, Inc. will exercise due diligence but will not be responsible for lost or destroyed samples or evidence unless client makes appropriate insurance coverage arrangements. Samples are held for thirty days following issuance of report. Samples will be stored at client's expense, if authorized in writing.

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- Thermogravimetric analysis indicates that very little residual matter is left at 450°C. Several transition states were observed indicating the presence of different components in the liquid mixture.
- Gas Chromatograhy - Mass Spectroscopic Analysis indicates the presence of predominantly three varieties of hydrocarbons fractions and very small quantity (<1%) of phenolic derivatives as given below:
  - A) Hydrocarbon solvents containing predominantly hepatane $C_7H_{16}$ (39.74%.)
  - B) Xylene fraction containing toluene and $C_3$ aromatics as impurities (28.78%.)
  - C) Fuel oil distillate consisting of $C_{10}$ - $C_{23}$ hydrocarbons with a maxima at $C_{15}$ (31.10%.)
  - D) Phenolics derivatives, 0.38% which are most likely alkyl phenols. They are three sets of four compounds which are most probably homologous series. Their exact structures are difficult to deduce without further work.

CONCLUSIONS AND RECOMMENDATIONS:

On the basis of the above data, the following represent the opinions of this laboratory:

The sample liquid contains:

- A) Aliphatic $C_7$ hydrocarbons (39.74%.)
- B) Aromatic solvents, namely xylene with toluene and $C_3$ aromatic as impurities (28.78%.)
- C) Fuel oil distillates, $C_{10}$ to $C_{23}$ hydrocarbons (31.10%.)
- D) A homologous series of alkyl substituted phenolic compounds (0.38%.)
- E) Residual ash 1.32%.

This report is rendered upon all of the following conditions: Skinner & Sherman Laboratories, Inc. retains ownership of this report until associated submitted invoice is satisfied. Expert witness services shall be available in conjunction with this report only if prior notification of this potential requirement was made and accepted, before the analysis. This report is not to be reproduced wholly or in part without special permission in writing. Total liability is limited to the invoice amount. Skinner & Sherman, Inc., Skinner & Sherman Technology, Inc., and/or New England Laboratories name and/or logos may not be used in conjunction with the contents of this report in any advertising media. The results listed refer only to tested samples and applicable parameters. Product endorsement is neither inferred nor implied. Skinner & Sherman Laboratories, Inc. will exercise due diligence but will not be responsible for lost or destroyed samples or evidence unless client makes appropriate insurance coverage arrangements. Samples are held for thirty days following issuance of report. Samples will be stored at client's expense, if authorized in writing.

TECHNICAL REPORT

19 May 1987

Page 3 of 3

CLIENT: Acurex Corporation

CASE NO:

It is recommended that the following work be carried out to fully characterize the sample mixture.

Analysis of the ash by Emission Spectroscopy to determine the nature of inorganic constituents.

Separate analysis of the ASA-3 additive to elucidate the structure of the phenolic components.

Copies of TGA graph and ion chromatograms are enclosed.

Respectfully submitted,

SKINNER AND SHERMAN LABORATORIES, INC.

Awinash Manmade

Awinash Manmade, Ph.D.
Chemist

AM/cd

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PART NO. 900326

DU PONT INSTRUMENTS

SAMPLE: 19194

ORIGIN: Acurex Corp

SIZE 16.2 mg

REF.

PROGRAM MODE heat

RATE 10 °C/MIN, START RT °C

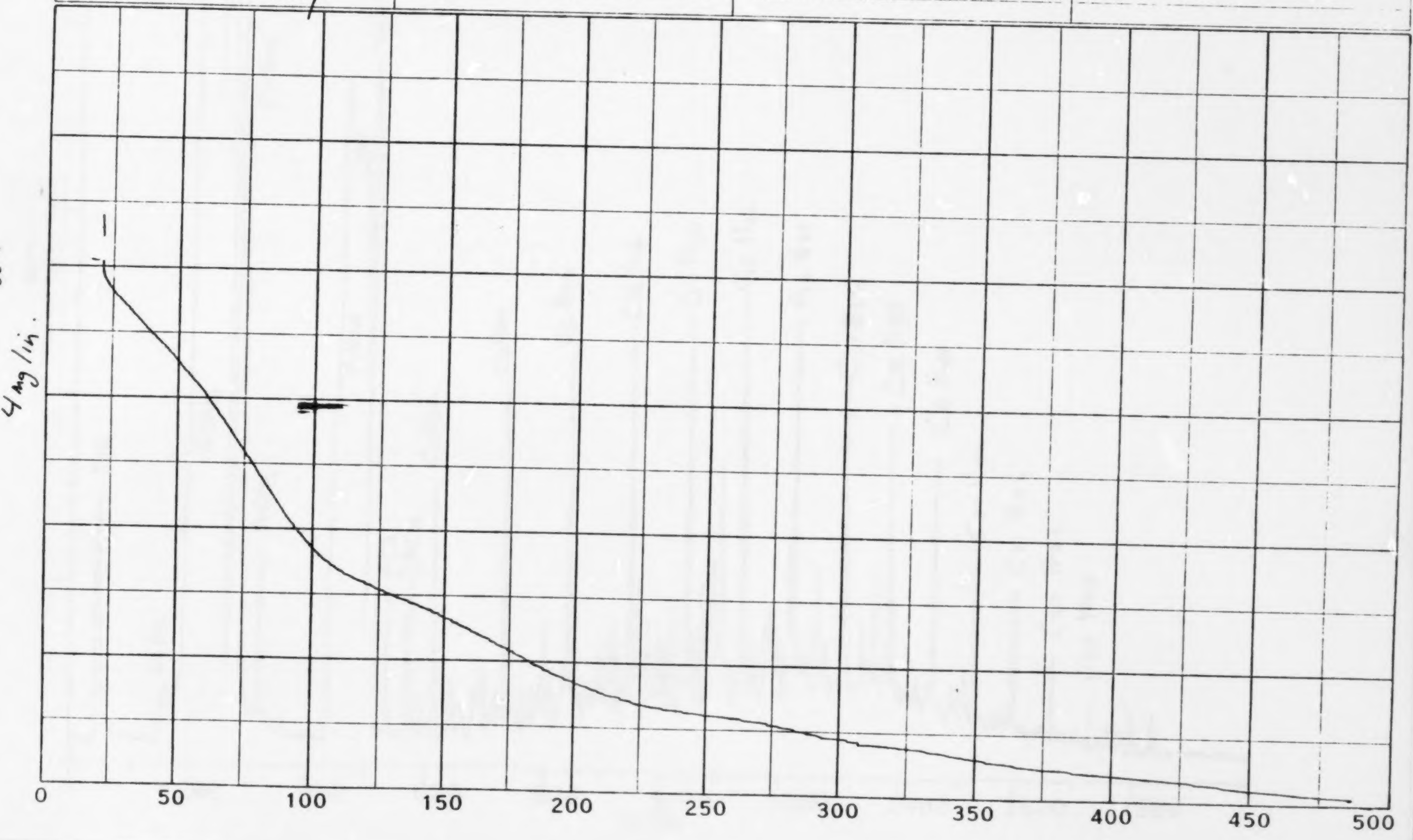
ATM. N$_2$ @ cc/min

| | T | ΔT |
|---|---|---|
| SCALE SETTING | 50 °C/IN | 4 mg/IN |

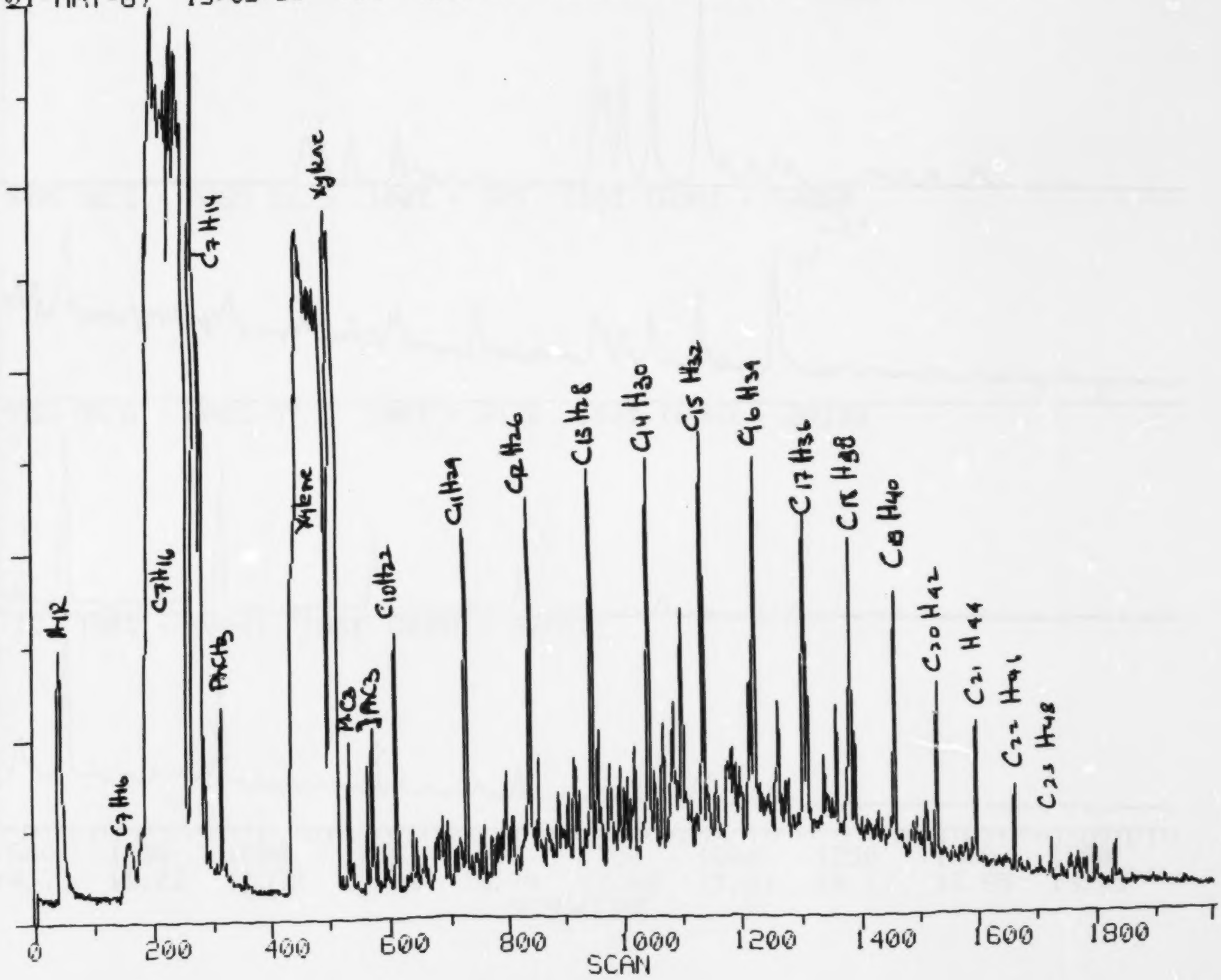
RUN NO. 1

DATE 5/11/87

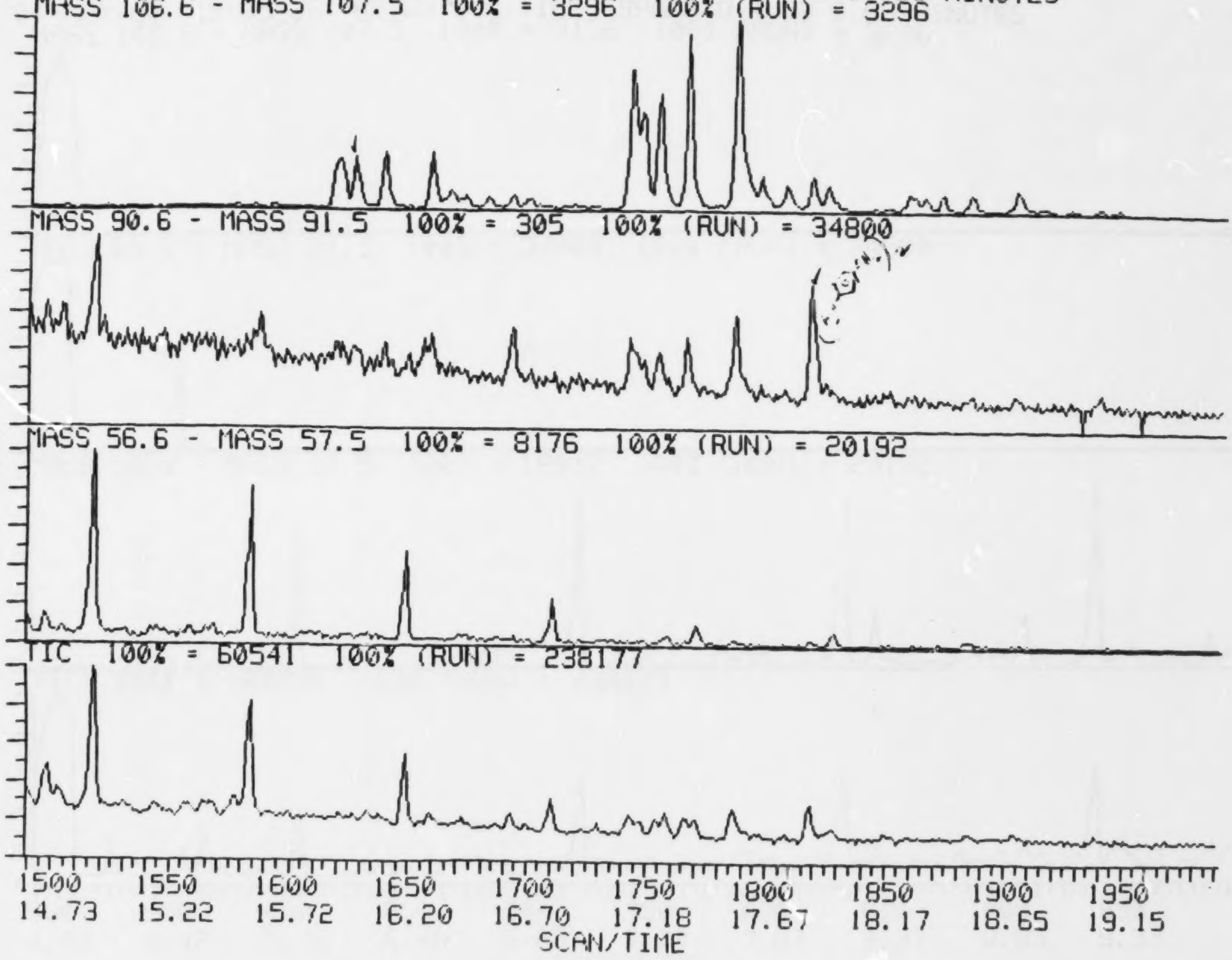
OPERATOR ADM



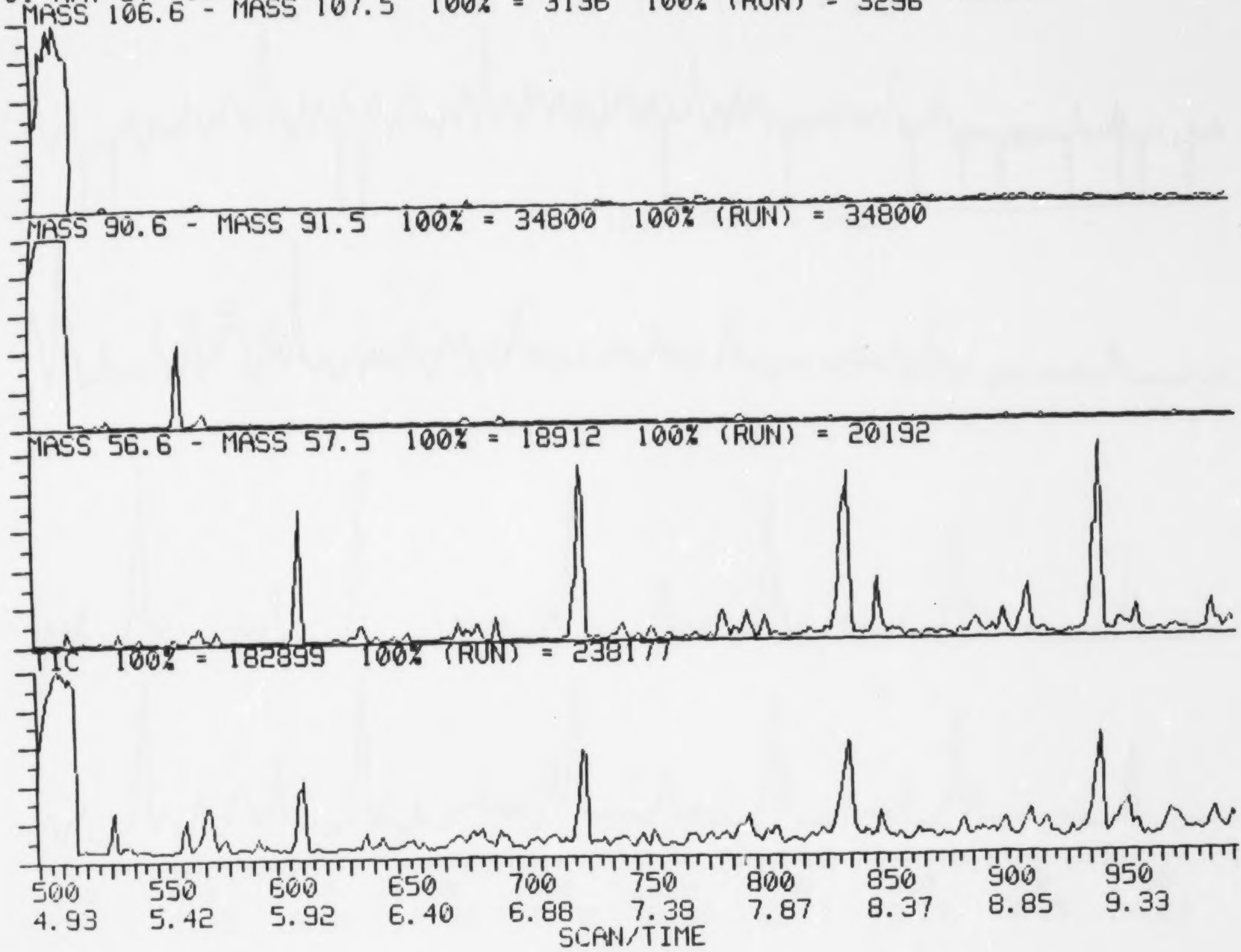
191941A 0.4uL SAMPLE, NEAT; GASGCMS; M=3; DB5-3, 35[1M]-300C@15C/M
01-MAY-87  15:05:36  TIC  MAXIMUM CURRENT=238177

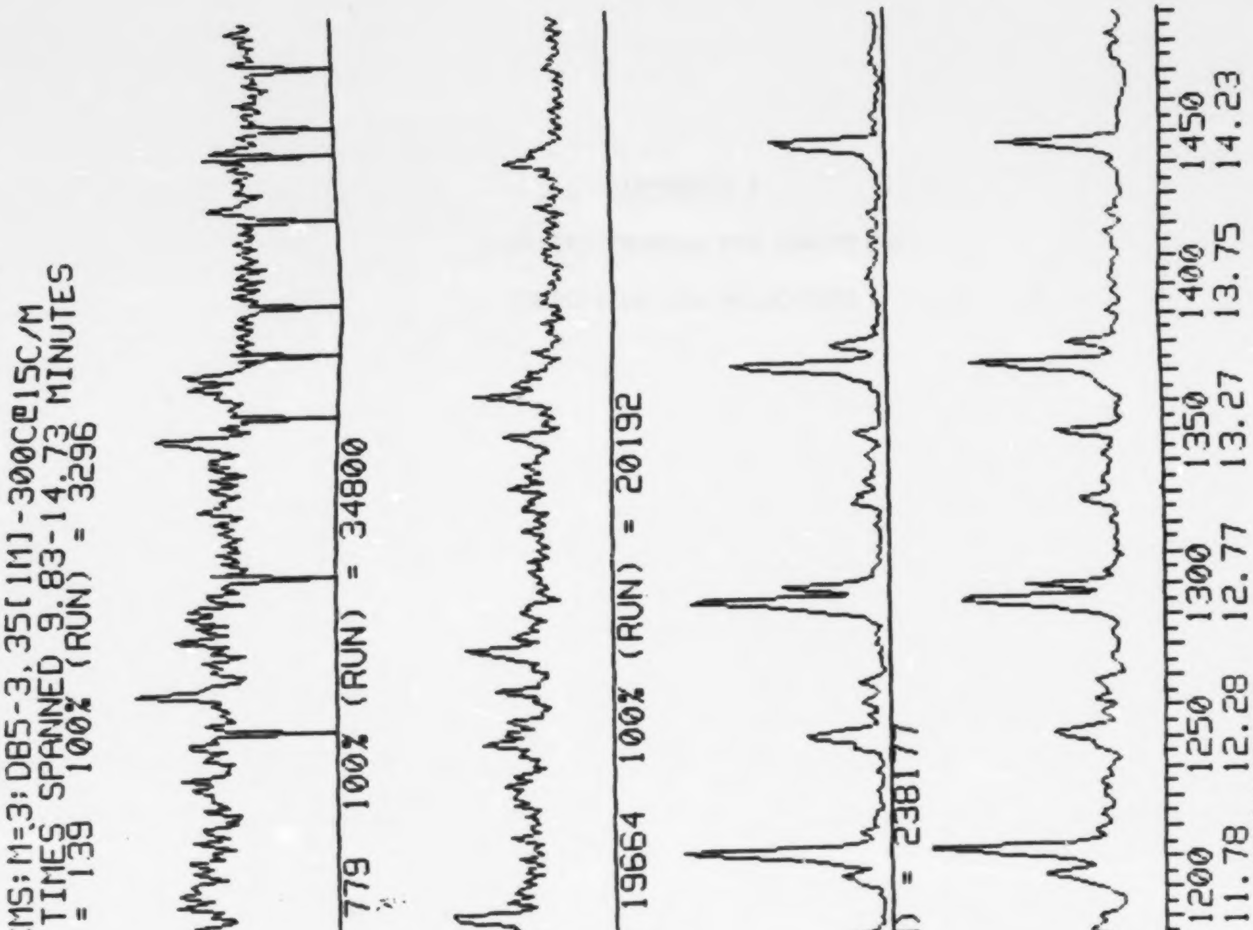


191941A 0.4uL SAMPLE, NEAT; GASGCMS; N=3; DB5-3, 35[1M]-300C@15C/M
01-MAY-87 15:05:36 RETENTION TIMES SPANNED 14.73-19.63 MINUTES



191941A 0.4uL SAMPLE, NEAT; GASGCMS; M=3; DB5-3, 35[1M]-300C@15C/M
01-MAY-87 15:05:36 RETENTION TIMES SPANNED 4.93-9.83 MINUTES




191941A 0.4uL SAMPLE, NEAT; GASGCMS; M=3; DB5-3,35[1M]-300C@15C/M
01-MAY-87 15:05:36 RETENTION TIMES SPANNED 9.83-14.73 MINUTES
MASS 106.6 - MASS 107.5 100% = 139 100% (RUN) = 3296
MASS 90.6 - MASS 91.5 100% = 779 100% (RUN) = 34800
MASS 56.6 - MASS 57.5 100% = 19664 100% (RUN) = 20192
TIC 100% = 124906 100% (RUN) = 238177
1000
9.83
1050
10.32
1100
10.82
1150
11.30
1200
11.78
1250
12.28
1300
12.77
1350
13.27
1400
13.75
1450
14.23
SCAN/TIME

# APPENDIX B

# COMPUTER PROGRAM FOR COMPUTING COMBUSTION GAS VELOCITIES

```
]LIST

1  REM  PROGRAM PITOT8 READS VOLT
    AGE SIGNALS FROM 4 PRESSURE
    SENSORS
2  REM  MONITORING 4 PRESSURE DIF
    FERENTIALS FROM A 5 HOLE PIT
    OT PROBE.
3  REM  OPTIONAL SUBROUTINE VELCA
    L COMPUTES THE AVERAGE 3 DIM
    ENSIONAL
4  REM  VELOCITY AND STANDARD DEV
    IATION FROM THE READING AND
    THE INPUT
5  REM  TEMPERATURE AND PRESSURE
    SENSOR ZERO READINGS.
6  REM
10  REM  READ TIME AND DATE
11  REM
20 D$ =  CHR$ (4)
30  PRINT  CHR$ (13); CHR$ (4)"BL
    OAD DETAI13.DELAY,A$99D4,D1"

40  PRINT D$;"PR#5"
50  PRINT D$;"IN#5"
60  INPUT "%";T1$
70  PRINT D$;"PR#0"
71  PRINT D$;"IN#0"
72  REM
73  REM  INPUT DATA POINT INFORMA
    TION
74  REM
75  PRINT "INPUT DATA POINT NUMBE
    R"
76  INPUT ID
77  PRINT "INPUT AXIAL LOCATION (
    INCHES)"
78  INPUT AL
79  PRINT "INPUT RADIAL LOCATION
    (INCHES)"
80  INPUT RL
81  REM
85  REM  DIMENSION VARIABLES
86  REM
90  DIM X0%(1,1),X1%(1,1),X2%(1,1
    ),X3%(1,1),X1(250),X2(250),X
    3(250),X4(250)
91  REM
95  REM  INITIALIZE VARIABLES
96  REM
99  PRINT "INPUT NUMBER OF READIN
    GS PER CHANNEL (1 TO 250)"
100  INPUT N
101 P = 10000
105 NUM = 1
110 N1 = 100
120 N2 = 100
130 N3 = 100
131  REM
135  REM  FORMAT RAW DATA OUTPUT
136  REM
140  PR# 1
145  PRINT : PRINT
```

```
160  PRINT : PRINT
161  PRINT "DATA POINT # "ID
162  PRINT "AXIAL LOCATION = "AL"
      INCHES"
163  PRINT "RADIAL LOCATION = "RL
     " INCHES"
164  PRINT : PRINT
170  PRINT ; TAB( 20);
180  PRINT "RAW DATA: VOLTAGE REA
     DINGS"
190  PRINT "RUN"
200  PRINT "NO."; TAB( 9);
210  PRINT "#1"; TAB( 22);
220  PRINT "#2"; TAB( 35);
230  PRINT "#3"; TAB( 49);
240  PRINT "#4": PRINT
250  PR# 0
251  REM
255  REM  SET UP RAW DATA ARRAYS
256  REM
260 SLOT = 4
270 X0%(0,0) = SLOT:X0%(1,0) =  -
     NUM
280 X1%(0.0) = SLOT:X1%(1.0) =  -
     NUM
290 X2%(0,0) = SLOT:X2%(1,0) =  -
     NUM
300 X3%(0,0) = SLOT:X3%(1,0) =  -
     NUM
310 GAIN = 4
330 X0%(0,1) = 16 * GAIN
340 X1%(0,1) = 1 + 16 * GAIN
350 X2%(0,1) = 2 + 16 * GAIN
360 X3%(0,1) = 3 + 16 * GAIN
371  REM
375  REM  DATA ACQUISITION LOOP
376  REM
377  REM  READ IN RAW DATA
378  REM
380  FOR I = 1 TO N
390  POKE 8,1: CALL 39380
400  POKE 8,2: CALL 39380
410  POKE 8,3: CALL 39380
420  POKE 8,4: CALL 39380
421  GOTO 451
422  REM
425  REM  DELAY
426  REM
430  FOR J = 1 TO N1
440  WAIT  - 16384,N2,N3
450  NEXT J
451  REM
455  REM  CONVERT READINGS TO VOL
     TAGES
456  REM
460 X1(I) = ((X0%(1,1) - 2047) /
     2048) * 5
470 X2(I) = ((X1%(1,1) - 2047) /
     2048) * 5
480 X3(I) = ((X2%(1.1) - 2047) /
     2048) * 5
490 X4(I) = ((X3%(1,1) - 2047) /
     2048) * 5
491  REM
495  REM  PRINT RAW DATA
```

```
500  PR# 1
502 X1(I) =  INT (X1(I) * P) / P
503 X2(I) =  INT (X2(I) * P) / P
504 X3(I) =  INT (X3(I) * P) / P
505 X4(I) =  INT (X4(I) * P) / P
507  GOTO 560
510  PRINT I; TAB( 5);
520  PRINT X1(I); TAB( 13);
530  PRINT X2(I); TAB( 31);
540  PRINT X3(I); TAB( 45);
550  PRINT X4(I)
560  NEXT I
570  PR# 0
570  REM
575  REM  CALCULATE AVERAGE VOLTA
     GES
576  REM
580 W1 = 0
590 W2 = 0
600 W3 = 0
610 W4 = 0
620  FOR I = 1 TO N
630 W1 = W1 + (X1(I) / N)
640 W2 = W2 + (X2(I) / N)
650 W3 = W3 + (X3(I) / N)
660 W4 = W4 + (X4(I) / N)
670  NEXT I
671  REM
675  REM  PRINT AVERAGE VOLTAGES
676  REM
680  PR# 1
682 W1 =  INT (W1 * P) / P
683 W2 =  INT (W2 * P) / P
684 W3 =  INT (W3 * P) / P
685 W4 =  INT (W4 * P) / P
690  PRINT : PRINT "AVE="; TAB( 5
     );
700  PRINT W1; TAB( 18);
710  PRINT W2; TAB( 31);
720  PRINT W3; TAB( 45);
730  PRINT W4
735  PRINT "NUMBER OF READINGS =
     "N
740  PR# 0
741  REM
745  REM  OPTION TO GO TO SUBROUT
     INE VELCAL
746  REM
750  INPUT "CONTINUE/STOP (1/0) "
     ;Q1
760  IF Q1 = 0 THEN 800
770  GOSUB 1000
800  END
900  REM
901  REM  SUBROUTINE VELCAL COMPU
     TES INSTANTANEOUS AND AVERAG
     E 3 DIMENSIONAL
902  REM  VELOCITIES FROM DATA FR
     OM THE MAIN PROGRAM AND FROM
      INPUT TEMPERATURES
903  REM  AND PRESSURE SENSOR ZER
     O READINGS.
904  REM
905  REM  A1,A3,A5 ARE CALIBRATIO
     N CONSTANTS.

906  REM
```

```
1000 A1 = 38.525864
1010 A3 = 29.7702999
1020 A5 =  - 11.3706318
1030  REM
1031  REM  B0,B2,B4 ARE CALIBRATI
     ON CONSTANTS.
1032  REM
1040 B0 = 0.693577988
1050 B2 =  - 6.68787948E - 05
1060 B4 = 1.76019925E - 06
1070  REM
1071  REM  INPUT DATA:
1072  REM  T=TEMPERATURE (DEGREES
      R)
1073  REM  D=DENSITY (LB/CU FT)
1074  REM  Z1=P0-P3 ZERO (VOLTS)

1075  REM  Z2=P0-P4 ZERO (VOLTS)
1076  REM  Z3=P2-P4 ZERO (VOLTS)
1077  REM  Z4=P1-P3 ZERO (VOLTS)
1078  REM  D1=P0-P3 (TORR)
1079  REM  D2=P0-P4 (TORR)
1080  REM  D3=P2-P4 (TORR)
1081  REM  D4=P1-P3 (TORR)
1082  REM  D5=P0-P1 (TORR)
1083  REM  D6=P0-P2 (TORR)
1084  REM  E=PROBE BEND (DEGREES)

1085  REM  F=PROBE ANGLE (DEGREES
     )
1086  REM
1090  PRINT "TEMPERATURE (DEGREES
      F) "
1100  INPUT T
1110 TR = T + 460
1120  PRINT "PRESSURE # 1 ZERO (V
     OLTS) "
1130  INPUT Z1
1140  PRINT "PRESSURE # 2 ZERO (V
     OLTS) "
1150  INPUT Z2
1160  PRINT "PRESSURE # 3 ZERO (V
     OLTS) "
1170  INPUT Z3
1180  PRINT "PRESSURE # 4 ZERO (V
     OLTS) "
1190  INPUT Z4
1200 E = 12
1210 ER = E * 2 * 3.1416 / 360
1220  PRINT "PROBE ANGLE (DEGREES
     ) "
1230  INPUT F
1240 FR = F * 2 * 3.1416 / 360
1250  REM
1251  REM  PRINT INPUT DATA
1252  REM
1260  PR# 1
1270  PRINT : PRINT
1280  PRINT "TEMPERATURE = "T" DE
     GREES F"
1290  PRINT "ZERO # 1 = "Z1" VOLT
     S"
1300  PRINT "ZERO # 2 = "Z2" VOLT
     S"
1310  PRINT "ZERO # 3 = "Z3" VOLT

      S"
```

```
1320  PRINT "ZERO # 4 = "Z4" VOLT
     S"
1330  PRINT "PROBE BEND = "E" DEG
     REES"
1340  PRINT "PROBE ANGLE = "F" DE
     GREES"
1350  PR# 0
1360  REM
1361  REM  INITIALIZE VARIABLES
1362  REM
1370 XX = 0
1371 YY = 0
1372 ZZ = 0
1373 AA = 0
1374 BB = 0
1375 VV = 0
1380 XW = 0
1381 YW = 0
1382 ZW = 0
1383 AW = 0
1384 BW = 0
1386 WW = 0
1400 SX = 0
1401 SY = 0
1402 SZ = 0
1403 SV = 0
1404 DX = 0
1405 DY = 0
1406 DZ = 0
1407 DV = 0
1410  REM
1411  REM  CALCULATE VELOCITIES
1412  REM
1420 D = 1 / ((0.7302 / 28) * TR)

1430  FOR I = 1 TO N
1440 D1 = (X1(I) - Z1) * (0.51715
      / 2.5)
1450 D2 = (X2(I) - Z2) * (0.51715
      / 2.5)
1460 D3 = (X3(I) - Z3) * (0.51715
      / 2.5)
1470 D4 = (X4(I) - Z4) * (0.51715
      / 2.5)
1480 D5 = D1 - D4
1490 D6 = D2 - D3
1500 PT = D5 + D6 + D1 + D2
1510 PR =  SQR (D5 ^ 2 + D6 ^ 2 +
     D1 ^ 2 + D2 ^ 2)
1520 KB =  SQR (1 - (PT / (2 * PR
     )))
1530  IF D4 = 0 GOTO 1550
1540  GOTO 1580
1550  IF D3 > 0 THEN AR =  - 1.57
     08
1560  IF D3 <  = 0 THEN AR = 1.57
     08
1570  GOTO 1590
1580 AR =  ATN ( - (D3 / D4))
1590 A = AR * 360 / (2 * 3.1416)
1600 B = (A1 * KB) + (A3 * KB ^ 3
     ) + (A5 * KB ^ 5)
1610 BR = B * 2 * 3.1416 / 360
1620 KV = B0 + (B2 * B ^ 2) + (B4
      * B ^ 4)

1630  V =  SQR (2 * KV * PR / D) * 9.469
```

```
1640 VX =  COS (BR) * V
1650 VY =  SIN (BR) *  COS (AR) *
     V
1655  IF D4 > 0 THEN VY =  - VY
1660 VZ =  SIN (BR) *  SIN (AR) *
     V
1665  IF D3 < 0 THEN VZ =  -  ABS
     (VZ)
1666  IF D3 >  = 0 THEN VZ =  ABS
     (VZ)
1670  REM
1671  REM  CORRECT VELOCITIES TO
     FIXED COORDINATE SYSTEM.
1672  REM
1685 WX = (VX *  COS (ER) - VY *
      SIN (ER)) *  COS (FR) - VZ *
      SIN (FR)
1695 WY = VY *  COS (ER) + VX *  SIN
     (ER)
1705 WZ = VZ *  COS (FR) + (VX *
      COS (ER) - VY *  SIN (ER)) *
      SIN (FR)
1710  DEF  FN ACS(X) =  -  ATN (X
      /  SQR ( - X * X + 1)) + 1.
     5707633
1725 WB =  FN ACS(WX / V)
1735 WA = ( FN ACS(WY / (V *  SIN
     (WB))) * 360) / (2 * 3.1416)

1740  IF WZ < 0 THEN WA = 360 - W
     A
1745 WB = WB * 360 / (2 * 3.1416)

1755 YZW =  SQR ((WY ^ 2) + (WZ ^
     2))
1770  REM
1771  REM  COMPUTE AVERAGES
1772  REM
1780 XX = XX + (VX / N)
1781 YY = YY + (VY / N)
1782 ZZ = ZZ + (VZ / N)
1783 AA = AA + (A / N)
1784 BB = BB + (B / N)
1786 VV = VV + (V / N)
1790 XW = XW + (WX / N)
1791 YW = YW + (WY / N)
1792 ZW = ZW + (WZ / N)
1793 AW = AW + (WA / N)
1794 BW = BW + (WB / N)
1796 WW = WW + (YZW / N)
1810 SX = SX + WX ^ 2
1811 SY = SY + WY ^ 2
1812 SZ = SZ + WZ ^ 2
1813 SV = SV + V ^ 2
1820  NEXT I
1830  REM
1831  REM  CALCULATE STANDARD DEV
     IATIONS
1832  REM
1840  IF N = 1 THEN  GOTO 1890
1850 DV2 =  SQR (((SV / (N - 1)) -
     (((VV * N) ^ 2) / (N * (N -
     1)))) ^ 2)
1855 DV =  SQR (DV2)

1860 DX2 = SQR ((SX / (N-1)) -
     (((XW * N) ^ 2) / (N * (N -
     1)))) ^ 2)
```

```
1865 DX =  SQR (DX2)
1870 DYZ =  SQR (((SY / (N - 1)) -
     (((YW * N) ^ 2) / (N * (N -
     1)))) ^ 2)
1875 DY =  SQR (DY2)
1880 DZZ =  SQR (((SZ / (N - 1)) -
     (((ZW * N) ^ 2) / (N * (N -
     1)))) ^ 2)
1885 DZ =  SQR (DZ2)
1890  REM
1891  REM  PRINT RESULTS
1892  REM
1900  PR# 1
1910  PRINT : PRINT
1920 P = 100
1930 XX =  INT (XX * P) / P
1931 YY =  INT (YY * P) / P
1932 ZZ =  INT (ZZ * P) / P
1933 AA =  INT (AA * P) / P
1934 BB =  INT (BB * P) / P
1935 VV =  INT (VV * P) / P
1950 XW =  INT (XW * P) / P
1951 YW =  INT (YW * P) / P
1952 ZW =  INT (ZW * P) / P
1953 AW =  INT (AW * P) / P
1954 BW =  INT (BW * P) / P
1956 WW =  INT (WW * P) / P
1960 DX =  INT (DX * P) / P
1961 DY =  INT (DY * P) / P
1962 DZ =  INT (DZ * P) / P
1963 DV =  INT (DV * P) / P
1969  PRINT "RAW DATA:"
1970  PRINT "GEOGRAPHIC LATITUDE
     = "BB" DEGREES"
1980  PRINT "VX = "XX" FEET PER S
     ECOND"
1990  PRINT "VY = "YY" FEET PER S
     ECOND"
2000  PRINT "VZ = "ZZ" FEET PER S
     ECOND"
2010  PRINT : PRINT
2120  PRINT "VELOCITY CALCULATION
     :"
2141 A9 = AW
2142 B9 = BW
2144 X9 = XW
2145 Y9 = YW
2146 Z9 = ZW
2147 V9 = WW
2150  PRINT
2160  PRINT "SPHERICAL COORINATES
     :"
2170  PRINT "V = "VV" FEET PER SE
     COND"
2180  PRINT "ANGLE A = "A9" DEGRE
     ES"
2190  PRINT "ANGLE B = "B9" DEGRE
     ES"
2191  FOR I = 1 TO 2
2192  IF I = 1 THEN  GOTO 2280
2193 X9 = VV *  COS (B9 * 2 * 3.1
     416 / 360)
2194 Y9 = VV *  SIN (B9 * 2 * 3.1
     416/ 360) * COS (A9 * 2 *
     3.1416 /360)
```

```
2195 Z9 = VV *  SIN (B9 * 2 * 3.1
     416 / 360) *  SIN (A9 * 2 *
     3.1416 / 360)
2196 V9 =  SQR ((Y9 ^ 2) + (Z9 ^
     2))
2198  PRINT
2199  PRINT "VELOCITY CALCULATION
      FROM SPHERICAL COORDINATE A
     VERAGES:"
2200  PRINT "RECTANGULAR COORDINA
     TES:"
2201 P = 100
2202 X9 =  INT (X9 * P) / P
2203 Y9 =  INT (Y9 * P) / P
2204 Z9 =  INT (Z9 * P) / P
2205 V9 =  INT (V9 * P) / P
2206 A9 =  INT (A9 * P) / P
2210  PRINT "VX = "X9" FEET PER S
     ECOND"
2220  PRINT "VY = "Y9" FEET PER S
     ECOND"
2230  PRINT "VZ = "Z9" FEET PER S
     ECOND"
2240  PRINT "CYLINDRICAL COORDINA
     TES:"
2250  PRINT "VX = "X9" FEET PER S
     ECOND"
2260  PRINT "VYZ = "V9" FEET PER
     SECOND"
2270  PRINT "ANGLE A = "A9" DEGRE
     ES"
2280  NEXT I
2290  PRINT : PRINT
2300  PRINT "STANDARD DEVIATIONS:
     "
2310  PRINT "STANDARD DEVIATION O
     F V = "DV
2320  PRINT "STANDARD DEVIATION O
     F VX = "DX
2330  PRINT "STANDARD DEVIATION O
     F VY = "DY
2340  PRINT "STANDARD DEVIATION O
     F VZ = "DZ
2350  PR# 0
2400  RETURN
```

# APPENDIX C

# COLD FLOW TESTS

# APPENDIX C1

## CONDENSED DATA SHEETS

COLD FLOW DROPLET TRAJECTORY DATA

| Date/Fluid | D (μm) | $l_{ds}$ (μm) | N | $V^{o}$ (m/s) | Experiment H (cm) | Experiment R (cm) |
|---|---|---|---|---|---|---|
| 11/22, 25/85 | 210 | 500 | 1 | 7.00 | 18.1 | 76 |
| ASA + No. 2 | " | " | 2 | " | " | 51 |
| (80/20) | " | " | 4 | " | " | 47 |
| | " | " | 8 | " | " | 39 |
| | " | " | 16 | " | " | 36 |
| | " | " | 32 | " | " | 31 |
| (repeated on 12/13) | " | " | 64 | " | " | 27 |
| | " | " | 128 | " | " | 26 |
| | " | " | 256 | " | " | 25 |
| | " | " | 512 | " | " | 25 |
| 11/22, 25/85 | 210 | 540 | 64 | 7.56 | 18.1 | 38 |
| | 210 | 710 | 64 | 9.80 | 18.1 | 43 |
| 12/11/85 | 180 | 390 | 64 | 5.46 | 18.1 | 24 |
| | 210 | 620 | 64 | 8.68 | 18.1 | 69 |
| 12/12/85 | 270 | 680 | 64 | 9.52 | 18.1 | 58 |
| | 330 | 660 | 64 | 9.24 | 18.1 | 74 |
| 2/6, 7/86 | 210 | 580 | 1 | 8.12 | 8.89 | 71 |
| ASA + No. 2 | " | " | 2 | " | 7.94 | 61 |
| (80/20) | " | " | 4 | " | " | 46 |
| | " | " | 8 | " | " | 42 |
| | " | " | 16 | " | " | 40 |
| | " | " | 32 | " | " | 38 |
| | " | " | 64 | " | " | 38 |
| | " | " | 128 | " | " | 38 |
| | " | " | 256 | " | " | 38 |
| | " | " | 512 | " | " | 38 |
| 2/6, 7/86 | 220 | 720 | 1 | 10.08 | 8.89 | 71 |
| | " | " | 2 | " | " | 71 |
| | " | " | 4 | " | " | 56 |
| | " | " | 8 | " | " | 54 |
| | " | " | 16 | " | " | 54 |
| | " | " | 32 | " | " | 51 |
| | " | " | 64 | " | " | 48 |
| | " | " | 128 | " | " | 47 |
| | " | " | 256 | " | " | 47 |
| | " | " | 512 | " | " | 46 |

## COLD FLOW DROPLET TRAJECTORY DATA (continued)

|  |  |  |  |  | Experiment |  |
|---|---|---|---|---|---|---|
| Date/Fluid | D ($\mu$m) | $l_{ds}$ ($\mu$m) | N | $V^o$ (m/s) | H (cm) | R (cm) |
| 2/6, 7/86 | 190 | 480 | 1 | 6.72 | 8.89 | 56 |
| ASA + No. 2 | " | " | 2 | " | 8.57 | 46 |
| (80/20) | " | " | 4 | " | " | 38 |
|  | " | " | 8 | " | " | 32 |
|  | " | " | 16 | " | " | 28 |
|  | " | " | 32 | " | " | 27 |
|  | " | " | 64 | " | " | 23 |
|  | " | " | 128 | " | " | 23 |
|  | " | " | 256 | " | " | 22 |
|  | " | " | 512 | " | " | 22 |
| 2/24/86 | 215 | 630 | 1 | 8.82 | 7.30 | 81 |
| $H_2O + C_3H_8O_3$ | " | " | 2 | " | " | 79 |
| (50/50) | " | " | 4 | " | " | 71 |
|  | " | " | 8 | " | " | 61 |
|  | " | " | 16 | " | " | 56.5 |
|  | " | " | 32 | " | " | 56 |
|  | " | " | 64 | " | " | 49.5 |
|  | " | " | 128 | " | " | 49.5 |
|  | " | " | 256 | " | " | 49.5 |
|  | " | " | 512 | " | " | 49.5 |
|  | 210 | 500 | 1 | 7.00 | 7.30 | 71 |
|  | " | " | 2 | " | " | 66 |
|  | " | " | 4 | " | " | 58 |
|  | " | " | 8 | " | " | 51 |
|  | " | " | 16 | " | " | 48 |
|  | " | " | 32 | " | " | 45 |
|  | " | " | 64 | " | " | 43 |
|  | " | " | 128 | " | " | 43 |
|  | " | " | 256 | " | " | 43 |
|  | " | " | 512 | " | " | 42 |
| 2/28/86 | 215 | 545 | 1 | 7.63 | 0.03 | 2.5 |
| $H_2O + C_3H_8O_3$ | " | " | " | " | 0.28 | 12.7 |
| (75/25) | " | " | " | " | 0.54 | 22.9 |
|  | " | " | " | " | 1.30 | 33 |
|  | " | " | " | " | 2.06 | 43 |
|  | " | " | " | " | 2.83 | 53 |
|  | " | " | " | " | 4.60 | 64 |
|  | " | " | " | " | 6.89 | 74 |
|  | " | " | " | " | 7.91 | 84 |
|  | " | " | " | " | 10.95 | 94 |
|  | " | " | " | " | 13.49 | 104 |
|  | " | " | " | " | 14.76 | 99 |

## COLD FLOW DROPLET TRAJECTORY DATA (concluded)

| Date/Fluid | D ($\mu m$) | $l_{ds}$ ($\mu m$) | N 512 | $V^o$ (m/s) | Experiment | |
|---|---|---|---|---|---|---|
| | | | | | H (cm) | R (cm) |
| 2/28/86 | 415 | 705 | 1 | 9.87 | 0.03 | 2.5 |
| $H_2O + C_3H_8O_3$ | " | " | " | " | 0.28 | 12.7 |
| (75/25) | " | " | " | " | 0.54 | 22.9 |
| | " | " | " | " | 1.05 | 33 |
| | " | " | " | " | 1.30 | 43 |
| | " | " | " | " | 2.06 | 53 |
| | " | " | " | " | 2.83 | 64 |
| | " | " | " | " | 3.84 | 74 |
| | " | " | " | " | 4.86 | 84 |
| | " | " | " | " | 6.13 | 94 |
| | " | " | " | " | 7.65 | 104 |
| | " | " | " | " | 9.68 | 114 |
| | " | " | " | " | 11.97 | 124 |
| | " | " | " | " | 14.76 | 130 |
| 3/5/86 | 415 | 705 | 2 | 9.87 | 13.97 | 113 |
| $H_2O + C_3H_8O_3$ | " | " | 4 | " | " | 110 |
| (75/25) | " | " | 8 | " | " | 105 |
| | " | " | 16 | " | " | 98 |
| | " | " | 32 | " | " | 95 |
| | " | " | 64 | " | " | 90 |
| | " | " | 128 | " | " | 89 |
| | " | " | 256 | " | " | 86 |
| | " | " | 512 | " | " | 86 |
| | 415 | 705 | 64 | 9.87 | 0.25 | 3.8 |
| | " | " | " | " | 0.51 | 14.0 |
| | " | " | " | " | 0.76 | 24 |
| | " | " | " | " | 1.27 | 34 |
| | " | " | " | " | 2.29 | 44.5 |
| | " | " | " | " | 3.56 | 55 |
| | " | " | " | " | 5.84 | 65 |
| | " | " | " | " | 13.49 | 90 |
| 3/6/86 | 215 | 545 | 64 | 7.63 | 0.16 | 8.3 |
| $H_2O + C_3H_8O_3$ | " | " | " | " | 0.32 | 13.3 |
| (75/25) | " | " | " | " | 0.95 | 23.5 |
| | " | " | " | " | 2.86 | 34 |
| | " | " | " | " | 7.94 | 44 |
| | " | " | " | " | 13.0 | 50 |

## COLD FLOW DRAG TESTS

| Liquid | $Re^o$ | $l^o/D$ | Comments | Date |
|---|---|---|---|---|
| ASA + No. 2 | 96 | 2.4 - 1219 (10 pts) | One-point trajectory | 11/22 |
| (80/20) | 104 | 165 | " | " |
| | 134 | 216 | " | " |
| | 64 | 139 | " | 12/11 |
| | 119 | 189 | " | " |
| | 168 | 161 | " | 12/12 |
| | 199 | 128 | " | " |
| | 111 | 2.8 - 1414 (10 pts) | " | 2/6 |
| | 145 | 3.3 - 1676 (10 pts) | " | " |
| | 83 | 2.5 - 1293 (10 pts) | " | " |
| Water + Glycerine | 124 | 2.9 - 1500 (10 pts) | One-point trajectory | 2/24 |
| (50/50) | 96 | 2.4 - 1219 (10 pts) | " | " |
| Water + Glycerine | 107 | 2.5 | Complete trajectory | 2/28 |
| (75/25) | 267 | 1.7 | " | |
| Water + Glycerine | 267 | 3.4 - 870 (9 pts) | One-point trajectory | 3/5 |
| (75/25) | 267 | 109 | Complete trajectory | 3/5 |
| | 107 | 162 | " | 3/6 |

$$64 \le Re^o \le 267$$
$$1.7 \le l^o/D \le 1676$$

# APPENDIX C2

# COLD FLOW TESTS

# COMPUTER PROGRAM

```
      PROGRAM TRAJ2
C
C        JIM MULHOLLAND, 1/22/87
C
C        PURPOSE:  TO CALCULATE DROPLET STREAM
C                  TRAJECTORIES IN 2-DIMENSIONAL COLD FLOW
C                  USING BEST-FIT DRAG COEFFICIENT PARAMETERS.
C                  THIS PROGRAM 2 PREDICTS THE FULL TRAJECTORY.
C
C        CD = LOCAL DRAG COEFFICIENT
C        RE = LOCAL REYNOLDS NUMBER
C        VT = MAGNITUDE OF TOTAL VELOCITY VECTOR
C        D = DROP DIAMETER
C        DS = DROP SPACING
C        N = NUMBER OF DROP DIVISIONS
C        VINIT = INITIAL DROP VELOCITY
C        SDINIT = INITIAL DROP SPACING
C        ARHO = DENSITY OF AIR
C        DRHO = DENSITY OF LIQUID DROP
C        ANU = KINEMATIC VISCOSITY OF AIR
C        A1,B1,A2,B2,A3,B3,A4,B4 = CD CONSTANTS
C        X = HORIZONTAL DISTANCE
C        Y = VERTICAL DISTANCE
C        YP = F1(1) = PREDICTED HORIZONTAL DISTANCE
C        VX = F1(2) = HORIZONTAL VELOCITY
C        VY = F1(3) = VERTICAL VELOCITY
C        T = F1(4) = TIME
C        F2(1) = DY/DX
C        F2(2) = DVX/DX
C        F2(3) = DVY/DX
C        F2(4) = DT/DX
C
C        P1,P2,P3,P4,P5,P6 = DRAG COEFFICIENT PARAMETERS
C
C        X1,X2,X3 = INTEGRATION STEP SIZE (HORIZONTAL DISTANCE)
C        XEND = INTEGRATION TERMINATION (HORIZONTAL DISTANCE)
C        YEND = INTEGRATION TERMINATION (VERTICAL DISTANCE)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER RUNGE
      DIMENSION F1(4),F2(4)
      OPEN (15,FILE='TRAJ2.DAT',STATUS='OLD')
      OPEN (17,FILE='TRAJ2.RS1',STATUS='NEW')
      OPEN (18,FILE='TRAJ2.RS2',STATUS='NEW')
C
C        READ, PRINT AND STORE MODEL INPUT DATA
C
      READ (15,100) N1,X1,X2,X3,XEND,YEND,P1,P2,P3,P4,P5,P6,
     1  D,FREQ,SDINIT,N,DRHO,FLOW
100   FORMAT (12X,I5/ 12X,F10.5,12X,F10.5,12X,F10.5/
     1  12X,F10.5,12X,F10.5/ 12X,F10.5,12X,F10.5,12X,F10.5/
     1  12X,F10.5,12X,F10.5,12X,F10.5/
     1  12X,F10.5/ 12X,F10.5/ 12X,F10.5/ 12X,I7/ 12X,F10.5/ 12X,F10.5)
      RATIO = ((SDINIT + D)/D) * N
      D = 100.0*((100.0*FLOW)/(3.1416*FREQ))**(1.0/3.0)
      SDINIT = RATIO * D
      VINIT = (SDINIT*FREQ)/(1000.0*N)
      REINIT = D*VINIT/15.33
      WRITE (*,101) N1,X1,X2,X3,XEND,YEND,P1,P2,P3,P4,P5,P6,
     1  D,VINIT,REINIT,RATIO
101   FORMAT ('  TRAJECTORY # = ',I5//
     1   ' INTEGRATION STEP SIZE, X1 = ',F10.5,' CM'/
     1   ' INTEGRATION STEP SIZE, X2 = ',F10.5,' CM'/
     1   ' INTEGRATION STEP SIZE, X3 = ',F10.5,' CM'/
     1   ' INTEGRATION TERMINATION, X = ',F10.3,' CM'/
     1   ' INTEGRATION TERMINATION, Y = ',F10.3,' CM'/
     1   ' CD PARAMETERS: '/ '    P1 = ',F10.5/ '    P2 = ',F10.5/
     1   '    P3 = ',F10.5/ '    P4 = ',F10.5/ '    P5 = ',F10.5/
     1   '    P6 = ',F10.5// ' DROP DIAMETER = ',F10.5,' MICRONS'/
     1   ' INITIAL VELOCITY = ',F10.5,' M/S'/
     1   ' INITIAL RE = ',F7.2/ ' INITIAL L/D = ',F10.3/)
      WRITE(17,101) N1,X1,X2,X3,XEND,YEND,P1,P2,P3,P4,P5,P6,
     1  D,VINIT,REINIT,RATIO
      WRITE(18,101) N1,X1,X2,X3,XEND,YEND,P1,P2,P3,P4,P5,P6,
     1  D,VINIT,REINIT,RATIO
C
C         SET CD CONSTANTS
C
      A1 = 27.0
      B1 = -0.84
      A2 = 0.271
      B2 = 0.217
      A3 = 2.0
      B3 = 0.0
      A4 = 0.755
      B4 = -1.0
C
C         SET FLOWFIELD PROPERTIES
C
      ARHO = 1.20
      ANU = 1.533E-5
      GRAV = 9.81
C
C         CHANGE UNITS
C
      D = D/1000000.0
      SDINIT = SDINIT/1000000.0
      X1 = X1/100.0
      X2 = X2/100.0
      X3 = X3/100.0
      XEND = XEND/100.0
      YEND = -YEND/100.0
C
C         SET PARAMETER A
C
      A = 0.75*ARHO/(DRHO*D)
C
C         SET ZSTAR
C
      A8 = (1.0/((1.0/(0.95**P2)-1.0)**(1.0/P2)))
      CDISTAR = A1*(P6**B1)
      IF(P6.GE.80.0) CDISTAR = A2*(P6**B2)
      IF(P6.GE.10000.0) CDISTAR = A3*(P6**B3)
      CDISTAR = CDISTAR*P5
      CDOSTAR = A4*(P6**B4)*P3
      ZSTAR = (A8*CDISTAR-CDOSTAR)/(P1/(P6**P4))
      WRITE(*,112) ZSTAR,P6,VINIT,REINIT,RATIO
  112 FORMAT(' AT L/D - 1 = ',F10.5,' AND RE = ',F10.5,
     1  ' CD = 0.95 x CDI'//
     1  '    X (CM)    Y (CM)     T (SEC)     VX (M/S)    VY (M/S)    RE',
     1  '       L/D'/
     1  '     0.00      0.000       0.000',2X,F9.3,6X,'0.000',
     1  2X,F7.2,2X,F7.1)
      WRITE(17,112) ZSTAR,P6,VINIT,REINIT,RATIO
      WRITE(18,112) ZSTAR,P6,VINIT,RATIO
C
C         INITIALIZE VARIABLES
```

```
      XX = 0.0
      XSTEP = X1
      ISTEP = 0
      F1(1) = 0.0
      F1(2) = VINIT
      F1(3) = 0.0
      F1(4) = 0.0
      Y2 = 0.0
C
C        INTEGRATE ONE STEP AT A TIME
C
   30 K = RUNGE (4,F1,F2,XX,XSTEP)
C
C        IS STEP FINISHED?
C
      IF (K.NE.1) GO TO 40
C
C        CALCULATE INTERMEDIATE PROPERTIES
C
      YY = F1(1)
      VX = F1(2)
      VY = F1(3)
      T = F1(4)
C
      VT = (VX**2+VY**2)**0.5
      RE = D*VT/ANU
      DS = VT*SDINIT/VINIT
      IF(DS.LE.D) DS = D
      ZZ = DS/D
      Z = (DS-D)/D
      CIS = A1*(RE**B1)
      IF(RE.GE.80.0) CIS = A2*(RE**B2)
      IF(RE.GE.10000.0) CIS = A3*(RE**B3)
      CO = A4*(RE**B4)
      CIS = CIS*P5
      CO = CO*P3
      CON = (A8*CIS-CO)/(ZSTAR*P1/(RE**P4))
      IF(RE.LE.P6) CON = 1.0
      CR = CO+(Z*P1/(RE**P4))*CON
      CD = CR/((1.0+(CR/CIS)**P2)**(1.0/P2))
C
      F2(1) = VY/VX
      F2(2) = -A*CD*VT
      F2(3) = -(A*CD*VT*VY/VX)-(GRAV/VX)
      F2(4) = 1/VX
C
      GO TO 30
C
   40 CONTINUE
C
      ISTEP = ISTEP+1
      IF (ISTEP.GT.10000) GO TO 50
C
      XCM = XX*100.0
      YCM = F1(1)*100.0
      T = F1(4)
C
C        CHANGE STEP SIZE
C
      IF(YCM.LT.-10.0) XSTEP = X2
      IF(YCM.LT.-100.0) XSTEP = X3
C
C        PRINT AND STORE RESULTS
C
      WRITE(*.105) XCM.YCM.T.VX.VY.RE.ZZ
```

```
  105 FORMAT(1X,F7.2,2X,F8.3,2X,F8.3,2X,F9.3,2X,F9[illegible],F7.2,2X,F7.1)
      WRITE(17,105) XCM,YCM,T,VX,VY,RE,ZZ
C
      Z = XCM/5.0
      I2 = IDNINT(Z)
      Z = Z*100.0
      I3 = IDNINT(Z)
      Z = I3/100.0
      IF(I2.NE.Z) GO TO 45
      WRITE(18,105) XCM,YCM,T,VX,VY,RE,ZZ
   45 CONTINUE
C
C         IS SOMETHING AWRY?
C         IS X LESS THAN XEND?
C         IS Y LESS THAN YEND?
C
      IF(YCM.GT.Y2) GO TO 34
      Y2 = YCM
      IF(XX.GT.XEND) GO TO 35
      IF(F1(1).LT.YEND) GO TO 36
C
      GO TO 30
C
   34 CONTINUE
      WRITE(*,109) XCM,YCM
  109 FORMAT(/' DY > 0 -- SOMETHING WENT AWRY!'/
     1  ' X = ',F8.3/ ' Y = ',F12.3)
      WRITE(17,109) XCM,YCM
      WRITE(18,109) XCM,YCM
      GO TO 37
   35 CONTINUE
      X3 = XEND*100.0
      WRITE(*,110) X3,XCM,YCM
  110 FORMAT(/ ' X > ',F8.3/
     1  ' X = ',F8.3/ ' Y = ',F12.3)
      WRITE(17,110) X3,XCM,YCM
      WRITE(18,110) X3,XCM,YCM
      GO TO 37
   36 CONTINUE
      Y3 = YEND*100.0
      WRITE(*,111) Y3,XCM,YCM,T
  111 FORMAT(/ ' Y < ',F8.3/
     1  ' X = ',F8.3/ ' Y = ',F12.3/ ' T = ',F8.3)
      WRITE(17,111) Y3,XCM,YCM,T
      WRITE(18,111) Y3,XCM,YCM,T
   37 CONTINUE
C
C         FINISH PROGRAM
C
      GO TO 90
C
   50 CONTINUE
      WRITE (*,108)
  108 FORMAT (' ISTEP > 10000'/)
      WRITE (17,108)
      WRITE (18,108)
C
   90 CONTINUE
C
      CLOSE (15,STATUS = 'KEEP')
      CLOSE (17,STATUS = 'KEEP')
      CLOSE (18,STATUS = 'KEEP')
      STOP
      END
```

# APPENDIX D

# TWO DIMENSIONAL LAMINAR FLAME TESTS

# APPENDIX D1

# CONDENSED DATA SHEETS

### FLAT-FLAME BURNER
### DROPLET TESTS
### REDUCED DATA

| Test Type | Data Pt.# | Fluid | $D^o$ ($\mu m$) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Nominal | 1 | 80% ASA | 234 | 7.71 | 2.54 | - 1-1/2, 0 | 12, 5/8 | 1-3/4 |
| (SR=1.575) | 2 | 20% No.2 | | 7.27 | 4.79 | - 1-1/2, 0 | 11-1/2, 5/8 | |
| | 3 | | | 6.90 | 9.10 | - 1-1/2, 0 | 11-3/8, 1/2 | |
| | 4 | | | 6.63 | 17.5 | - 1-1/2, 0 | 11, 3/4 | |
| | 5 | | | 6.43 | 33.9 | - 1-1/2, 0 | 10, 7/8 | |
| | 6 | | | 6.30 | 66.4 | 6-3/8, 1/4 | 9-3/4, 3/4 | |
| | 7 | | | 6.22 | 131 | 7, 3/8 | 9-1/2, 1-1/4 | |
| | 8 | | | 6.16 | 260 | 7-5/8, 1/2 | 9-7/8, 1-1/4 | |
| | 9 | | | 6.13 | 517 | 7-5/8, 3/8 | 9-5/8, 1-1/4 | |
| | 10 | | | 6.11 | 1030 | 8-1/2, 11/16 | 9-3/8, 1-3/8 | |
| Liquid | 11 | 75% $H_2O$ | 237 | 7.62 | 2.56 | No Ignition | 12, 1/2 | 1-3/4 |
| | 12 | 25% $C_3H_8O_3$ | | 7.26 | 4.94 | | 12, 5/8 | |
| | 13 | | | 6.97 | 9.48 | | 12, 7/8 | |
| | 14 | | | 6.75 | 18.4 | | 12, 1 | |
| | 15 | | | 6.59 | 35.9 | | 12, 1-1/8 | |
| | 16 | | | 6.49 | 70.5 | | 12, 1-1/4 | |
| | 17 | | | 6.42 | 149 | | 12, 1-1/4 | |
| | 18 | | | 6.37 | 277 | | 12, 1-3/8 | |
| | 19 | | | 6.34 | 552 | | 12, 1-3/8 | |
| | 20 | | | 6.32 | 1101 | | 12, 1-3/8 | |

## FLAT-FLAME BURNER
## DROPLET TESTS
## REDUCED DATA (continued)

| Test Type | Data Pt.# | Fluid | $D^o$ ($\mu m$) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Medium | 21 | 80% ASA | 311 | 9.15 | 2.37 | -1 to 0, 0 | 12, 7/8 | 1-3/4 |
| Size | 22 | 20% No.2 | | 8.76 | 4.55 | -1 to 0, 0 | 12, 11/16 | |
| | 23 | | | 8.39 | 8.71 | -1 to 0, 0 | 12, 5/8 | |
| | 24 | | | 8.07 | 16.7 | - 1-1/2, 0 | 12, 3/4 | |
| | 25 | | | 7.82 | 32.5 | 6, 1/2 | 11, 1-1/8 | |
| | 26 | | | 7.64 | 63.4 | 5, 1/4 | 11-1/2, 3/4 | |
| | 27 | | | 7.51 | 125 | 10-1/2, 1/2 | 11-1/2, 7/8 | |
| | 28 | | | 7.43 | 151 | flicker | 11, 7/8 | |
| | 29 | | | 7.38 | 490 | flicker | 10, 3/4 | |
| | 30 | | | 7.35 | 976 | 10, 3/4 | 10, 3/4 | |
| Large | 31 | 80% ASA | 381 | 10.11 | 2.21 | -1 to 0, 0 | 12, 1/2 | 1-3/4 |
| Size | 32 | 20% No.2 | | 9.80 | 4.29 | – | – | |
| | 33 | | | 9.45 | 8.28 | -1 to 0, 0 | 12, 5/8 | |
| | 34 | | | 9.12 | 16.0 | -1 to 0, 0 | 12, 5/8 | |
| | 35 | | | 8.84 | 31.0 | - 1-1/4 to 0, 0 | 11-1/2, 11/16 | |
| | 36 | | | 8.63 | 60.4 | -1 to 0, 0 | 12, 3/4 | |
| | 37 | | | 8.48 | 119 | flicker | 11-1/4, 1-1/8 | |
| | 38 | | | 8.37 | 235 | flicker | 12, 1 | |
| | 39 | | | 8.31 | 465 | flicker | 11, 1-1/8 | |
| | 40 | | | 8.26 | 926 | 11, 7/8 | 11, 7/8 | |

### FLAT-FLAME BURNER
### DROPLET TESTS
### REDUCED DATA (continued)

| Test Type | Data Pt.# | Fluid | $D^o$ (μm) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Low Velocity | 41 | 80% ASA<br>20% No.2 | 193 | 6.34 | 2.12 | 5-3/8, 1/4 | 11-3/8, 1 | 1-3/4 |
| | 42 | | | 5.90 | 3.94 | 5-1/2, 3/16 | 11-3/8, 1-1/4 | |
| | 43 | | | 5.55 | 7.42 | 5, 5/16 | 9, 1-3/8 | |
| | 44 | | | 5.30 | 14.2 | 5, 3/8 | 11, 1-3/8 | |
| | 45 | | | 5.11 | 27.3 | 5-1/4, 1/2 | 10, 1-1/4 | |
| | 46 | | | 4.99 | 53.4 | 5-3/4, 3/4 | 7, 1-1/8 | |
| | 47 | | | 4.91 | 105 | 6-3/8, 7/8 | 7, 1 | |
| | 48 | | | 4.85 | 208 | 6-1/2, 7/8 | 6-7/8, 1-1/8 | |
| | 49 | | | 4.82 | 412 | 6-3/4, 3/4 | 6-7/8, 1 | |
| | 50 | | | 4.80 | 821 | 5-3/4, 5/8 | 6-3/4, 1 | |
| High Velocity | 51 | 80% ASA<br>20% No.2 | 264 | 9.15 | 2.94 | -1 to 0, 0 | 12, 5/16 | 1-3/4 |
| | 52 | | | 8.69 | 5.58 | – | – | |
| | 53 | | | 8.28 | 10.6 | -1 to 0, 0 | 11-1/2, 1/2 | |
| | 54 | | | 7.95 | 20.4 | -1 to 0, 0 | 11-1/2, 9/16 | |
| | 55 | | | 7.71 | 39.7 | - 1 to 0, 0 | 11-1/2, 9/16 | |
| | 56 | | | 7.55 | 77.6 | 7, 5/16 | 11, 5/8 | |
| | 57 | | | 7.44 | 153 | 8, 3/8 | 10-1/2, 3/4 | |
| | 58 | | | 7.37 | 303 | 8-1/4, 7/16 | 10, 3/4 | |
| | 59 | | | 7.32 | 602 | 8-3/4, 1/2 | 10, 5/8 | |
| | 60 | | | 7.30 | 1200 | 10-3/4, 3/4 | 10-3/4, 3/4 | |

### FLAT-FLAME BURNER
### DROPLET TESTS
### REDUCED DATA (continued)

| Test Type | Data Pt.# | Fluid | $D^o$ (μm) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Injection | 61 | 80% ASA | 235 | 7.63 | 2.54 | 5, 1/16 | 12, 3/16 | 3-1/2 |
| Location | 62 | 20% No.2 |  | 7.20 | 4.79 | 4-1/4, 1/32 | 12, 1/8 |  |
|  | 63 |  |  | 6.84 | 9.10 | 1-1/2, 1/32 | 11-3/8, 3/8 |  |
|  | 64 |  |  | 6.57 | 17.5 | 1-1/2, 1/32 | 11-1/2, 9/16 |  |
|  | 65 |  |  | 6.38 | 34.0 | 1, 0 | 11, 3/8 |  |
|  | 66 |  |  | 6.25 | 66.5 | 7-3/4, 3/32 | 11-1/8, 5/8 |  |
|  | 67 |  |  | 6.16 | 131 | 7-1/2, 3/16 | 8, 1/4 |  |
|  | 68 |  |  | 6.11 | 260 | 9-1/2, 1/2 | 9-1/2, 1/2 |  |
|  | 69 |  |  | 6.08 | 518 | 10, 7/16 | 10, 7/16 |  |
|  | 70 |  |  | 6.05 | 1032 | 10-1/4, 1/2 | 10-1/4, 1/2 |  |
| Injection | A | 80% ASA |  | 6.16 | 131 | No | 12, - | 5-3/8 |
| Location | B | 20% No.2 |  | 6.16 | 131 | Ignition | 12, - | 7-1/8 |

### FLAT-FLAME BURNER
### DROPLET TESTS
### REDUCED DATA (continued)

| Test Type | Data Pt.# | Fluid | $D^o$ (μm) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Liquid<br>(SR=1.43) | 71 | 75% $H_2O$<br>25% $C_3H_8O_3$ | 234 | 7.11 | 2.54 | No Ignition | 12, 1 | 1-3/4 |
| | 72 | | | 6.72 | 4.79 | | 12, 1-7/8 | |
| | 73 | | | 6.40 | 9.13 | " | 10-1/4, 4-5/8 | |
| | 74 | | | 6.16 | 17.6 | " | 10-1/4, 5 | |
| | 75 | | | 6.00 | 34.2 | " | 10-1/4, 5-3/4 | |
| | 76 | | | 5.89 | 67.2 | " | 10-1/4, 5-3/4 | |
| | 77 | | | 5.81 | 133 | " | 10-1/4, 6-3/4 | |
| | 78 | | | 5.77 | 263 | " | 8-3/4, 6-3/4 | |
| | 79 | | | 5.74 | 524 | " | 8-1/2, 7-1/4 | |
| | 80 | | | 5.72 | 1045 | " | 7-3/4, 11 | |
| Excess<br>Air<br>(SR=1.59) | 81 | 80% ASA<br>20% No.2 | 240 | 6.51 | 2.26 | - | 12, 15/16 | 1-3/4 |
| | 82 | | | 6.10 | 4.24 | - | 12, 7/8 | |
| | 83 | | | 5.78 | 8.04 | - | 12, 7/8 | |
| | 84 | | | 5.54 | 15.4 | - | 11-3/4, 7/8 | |
| | 85 | | | 5.38 | 29.9 | - | 11-5/8, 1 | |
| | 86 | | | 5.27 | 58.6 | - | 11-1/2, 1-1/16 | |
| | 87 | | | 5.20 | 116 | - | 11-5/8, 1-1/4 | |
| | 88 | | | 5.15 | 229 | - | 7, 1/2 | |
| | 89 | | | 5.12 | 456 | - | 7-1/4, 5/8 | |
| | 90 | | | 5.10 | 908 | - | 7-1/4, 3/4 | |

## FLAT-FLAME BURNER
## DROPLET TESTS
## REDUCED DATA (continued)

| Test Type | Data Pt.# | Fluid | D° (μm) | V° (m/s) | L°/D° | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Excess | 91 | 80% ASA | 240 | 6.51 | 2.26 | - | 12, 3/8 | 1-3/4 |
| Air | 92 | 20% No. 2 | | 6.10 | 4.24 | - | 12, 1/2 | |
| (SR=1.17) | 93 | | | 5.78 | 8.04 | - | 12, 7/8 | |
| | 94 | | | 5.54 | 15.4 | - | 12, 15/16 | |
| | 95 | | | 5.38 | 29.9 | - | 11-5/8, 3/4 | |
| | 96 | | | 5.27 | 58.6 | - | 11-1/4, 7/8 | |
| | 97 | | | 5.20 | 116 | - | 2, 1/8 | |
| | 99 | | | 5.15 | 229 | - | 2, 3/16 | |
| | 99 | | | 5.12 | 456 | - | 2-3/4, 3/8 | |
| | 100 | | | 5.10 | 908 | - | 2-5/8, 5/16 | |
| Excess | 101 | 80% ASA | 262 | 6.16 | 2.55 | -1 to 0, 0 | 12, 5/16 | 1-3/4 |
| Air | 102 | 20% No.2 | | 5.84 | 4.85 | 4-1/4, 1/32 | 12, 5/16 | |
| (SR=1.59) | 103 | | | 5.59 | 9.28 | 8-3/4, 1/4 | 12, 9/16 | |
| | 104 | | | 5.40 | 17.9 | 7-3/4, 5/16 | 11-1/4, 9/16 | |
| | 105 | | | 5.27 | 35.0 | 8, 5/16 | 11-1/4, 5/8 | |
| | 106 | | | 5.19 | 68.8 | 9-3/4, 1/2 | 11-1/4, 3/4 | |
| | 107 | | | 5.13 | 136 | 10-3/4, 3/4 | 11-1/4, 3/4 | |
| | 108 | | | 5.09 | 270 | 11-3/8, 7/8 | 11-1/4, 7/8 | |
| | 109 | | | 5.07 | 538 | 11-3/8, 1 | 11-3/8, 1 | |
| | 110 | | | 5.06 | 1074 | 11-3/8, 1-1/16 | 11-3/8, 1-1/16 | |

### FLAT-FLAME BURNER
### DROPLET TESTS
### REDUCED DATA (concluded)

| Test Type | Data Pt.# | Fluid | $D^o$ (µm) | $V^o$ (m/s) | $L^o/D^o$ | Ignition x,y | Burnout x,y | Inj. Pt. |
|---|---|---|---|---|---|---|---|---|
| Excess | 111 | 80% ASA | 251 | 6.25 | 2.37 | No | 12, 9/16 | 1-3/4 |
| Air | 112 | 20% No. 2 | | 5.91 | 4.49 | Luminous | 12, 5/8 | |
| (SR=0.99) | 113 | | | 5.64 | 8.57 | Ignition | 12, 3/4 | |
| | 114 | | | 5.44 | 16.5 | Point | 12, 9/16 | |
| | 115 | | | 5.30 | 32.2 | - | 12, 5/8 | |
| | 116 | | | 5.21 | 63.3 | - | 12, 3/4 | |
| | 117 | | | 5.15 | 125 | - | - | |
| | 118 | | | 5.11 | 249 | - | - | |
| | 119 | | | 5.09 | 495 | - | - | |
| | 120 | | | 5.07 | 986 | - | - | |

### FLAT-FLAME BURNER
### DROPLET TESTS
### INPUT DATA

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | (kg/m²) | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Nominal<br>(SR=1.575) | 10/03/86 | 1 | 80% ASA<br>20% No.2 | 5.2 | 25 | 45 | 13.0 | 859 | 10 | 1 |
| | | 2 | | | | | | | | ·2 |
| | | 3 | | | | | | | | 4 |
| | | 4 | | | | | | | | 8 |
| | | 5 | | | | | | | | 16 |
| | | 6 | | | | | | | | 32 |
| | | 7 | | | | | | | | 64 |
| | | 8 | | | | | | | | 128 |
| | | 9 | | | | | | | | 256 |
| | | 10 | | | | | | | | 512 |
| Liquid | 09/26/86 | 11 | 75% $H_2O$<br>25% $C_3H_8O_3$ | 5.2 | 25 | 50 | 12.4 | 1063 | 10 | 1 |
| | | 12 | | | | | | | | 2 |
| | | 13 | | | | | | | | 4 |
| | | 14 | | | | | | | | 8 |
| | | 15 | | | | | | | | 16 |
| | | 16 | | | | | | | | 32 |
| | | 17 | | | | | | | | 64 |
| | | 18 | | | | | | | | 128 |
| | | 19 | | | | | | | | 256 |
| | | 20 | | | | | | | | 512 |

### FLAT-FLAME BURNER
### DROPLET TESTS
### INPUT DATA (continued)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | (kg/m$^2$) | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Medium Size | 10/14/86 | 21 | 80% ASA<br>20% No.2 | 11.7 | 30 | 45 | 12.4 | 859 | 10 | 1 |
| | | 22 | | | | | | | | 2 |
| | | 23 | | | | | | | | 4 |
| | | 24 | | | | | | | | 8 |
| | | 25 | | | | | | | | 16 |
| | | 26 | | | | | | | | 32 |
| | | 27 | | | | | | | | 64 |
| | | 28 | | | | | | | | 128 |
| | | 29 | | | | | | | | 256 |
| | | 30 | | | | | | | | 512 |
| Large Size | 10/15/86 | 31 | 80% ASA<br>20% No.2 | 20.8 | 25 | 45 | 12.0 | 859 | 10 | 1 |
| | | 32 | | | | | | | | 2 |
| | | 33 | | | | | | | | 4 |
| | | 34 | | | | | | | | 8 |
| | | 35 | | | | | | | | 16 |
| | | 36 | | | | | | | | 32 |
| | | 37 | | | | | | | | 64 |
| | | 38 | | | | | | | | 128 |
| | | 39 | | | | | | | | 256 |
| | | 40 | | | | | | | | 512 |

### FLAT-FLAME BURNER
### DROPLET TESTS
### INPUT DATA (continued)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | $(kg/m^2)$ | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Low Velocity | 10/07/86 | 41 | 80% ASA<br>20% No.2 | 3.5 | 23 | 32 | 15.5 | 859 | 10 | 1 |
| | | 42 | | | | | | | | 2 |
| | | 43 | | | | | | | | 4 |
| | | 44 | | | | | | | | 8 |
| | | 45 | | | | | | | | 16 |
| | | 46 | | | | | | | | 32 |
| | | 47 | | | | | | | | 64 |
| | | 48 | | | | | | | | 128 |
| | | 49 | | | | | | | | 256 |
| | | 50 | | | | | | | | 512 |
| High Velocity | 10/15/86 | 51 | 80% ASA<br>20% No.2 | 6.8 | 25 | 55 | 11.8 | 859 | 10 | 1 |
| | | 52 | | | | | | | | 2 |
| | | 53 | | | | | | | | 4 |
| | | 54 | | | | | | | | 8 |
| | | 55 | | | | | | | | 16 |
| | | 56 | | | | | | | | 32 |
| | | 57 | | | | | | | | 64 |
| | | 58 | | | | | | | | 128 |
| | | 59 | | | | | | | | 256 |
| | | 60 | | | | | | | | 512 |

## FLAT-FLAME BURNER
## DROPLET TESTS
## INPUT DATA (continued)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | (kg/m²) | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | 10/06/86 | 61 | 80% ASA | 5.2 | 25 | 45 | 12.8 | 859 | 10 | 1 |
| | | 62 | 20% No.2 | | | | | | | 2 |
| | | 63 | | | | | | | | 4 |
| | | 64 | | | | | | | | 8 |
| | | 65 | | | | | | | | 16 |
| | | 66 | | | | | | | | 32 |
| | | 67 | | | | | | | | 64 |
| | | 68 | | | | | | | | 128 |
| | | 69 | | | | | | | | 256 |
| | | 70 | | | | | | | | 512 |
| Location | 10/06/86 | A | 80% ASA | 5.2 | 25 | 45 | 12.8 | 859 | 10 | 64 |
| | | B | 20% No.2 | 5.2 | 25 | 45 | 12.8 | 859 | 10 | 64 |

### FLAT-FLAME BURNER
### DROPLET TESTS
### INPUT DATA (continued)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | (kg/m²) | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Liquid | 12/09/86 | 71 | 75% $H_2O$ | 4.8 | 25 | 45 | 12.0 | 1063 | 12 | 1 |
| (SR=1.43) | | 72 | 25% $C_3H_8O_3$ | | | | | | | 2 |
| | | 73 | | | | | | | | 4 |
| | | 74 | | | | | | | | 8 |
| | | 75 | | | | | | | | 16 |
| | | 76 | | | | | | | | 32 |
| | | 77 | | | | | | | | 64 |
| | | 78 | | | | | | | | 128 |
| | | 79 | | | | | | | | 256 |
| | | 80 | | | | | | | | 512 |
| Excess | 12/18/86 | 81 | 80% ASA | 5.2 | 30 | 45 | 12.0 | 859 | 11 | 1 |
| Air | | 82 | 20% No.2 | | | | | | | 2 |
| (SR=1.59) | | 83 | | | | | | | | 4 |
| | | 84 | | | | | | | | 8 |
| | | 85 | | | | | | | | 16 |
| | | 86 | | | | | | | | 32 |
| | | 87 | | | | | | | | 64 |
| | | 88 | | | | | | | | 128 |
| | | 89 | | | | | | | | 256 |
| | | 90 | | | | | | | | 512 |

FLAT-FLAME BURNER
DROPLET TESTS
INPUT DATA (continued)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | (kg/m$^2$) | $x_i$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Excess Air (SR=1.17) | 12/18/86 | 91 | 80% ASA<br>20% No.2 | 5.2 | 30 | 45 | 12.0 | 859 | 11 | 1 |
| | | 92 | | | | | | | | 2 |
| | | 93 | | | | | | | | 4 |
| | | 94 | | | | | | | | 8 |
| | | 95 | | | | | | | | 16 |
| | | 96 | | | | | | | | 32 |
| | | 97 | | | | | | | | 64 |
| | | 98 | | | | | | | | 128 |
| | | 99 | | | | | | | | 256 |
| | | 100 | | | | | | | | 512 |
| Excess Air (SR=1.83) | 01/05/87 | 101 | 80% ASA<br>20% No.2 | 5.2 | 25 | 45 | 9.2 | 859 | 10 | 1 |
| | | 102 | | | | | | | | 2 |
| | | 103 | | | | | | | | 4 |
| | | 104 | | | | | | | | 8 |
| | | 105 | | | | | | | | 16 |
| | | 106 | | | | | | | | 32 |
| | | 107 | | | | | | | | 64 |
| | | 108 | | | | | | | | 128 |
| | | 109 | | | | | | | | 256 |
| | | 110 | | | | | | | | 512 |

### FLAT-FLAME BURNER
### DROPLET TESTS
### INPUT DATA (concluded)

| Test Type | Date | Data Pt.# | Fluid | Flow (ml/min) | D (div) | L (div) | Freq. (kHz) | ($kg/m^2$) | $x_l$ (cm) | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Excess | 01/06/87 | 111 | 80% ASA | 5.2 | 25 | 40 | 10.5 | 859 | 10 | 1 |
| Air | | 112 | 20% No.2 | | | | | | | 2 |
| (SR=0.99) | | 113 | | | | | | | | 4 |
| | | 114 | | | | | | | | 8 |
| | | 115 | | | | | | | | 16 |
| | | 116 | | | | | | | | 32 |
| | | 117 | | | | | | | | 64 |
| | | 118 | | | | | | | | 128 |
| | | 119 | | | | | | | | 256 |
| | | 120 | | | | | | | | 512 |

# APPENDIX D2

# COMPUTER PROGRAM

```
   1
FLAT FLAME TEST #1
  6   9
 0.02000 0.04000 0.08000 0.12000 0.16000 0.20000 0.24000 0.28000 0.3048
 0.06000 0.06000 0.06000 0.06000 0.06000 0.06000
 0.09808 0.08025 0.73964 0.08203
  0.241   0.254   0.267   0.275   0.281   0.278   0.273   0.267   0.254
  0.227   0.241   0.246   0.251   0.254   0.251   0.246   0.241   0.227
  0.203   0.214   0.219   0.225   0.227   0.225   0.219   0.214   0.203
  0.193   0.201   0.201   0.201   0.201   0.201   0.201   0.201   0.193
  0.168   0.174   0.174   0.174   0.174   0.174   0.174   0.174   0.168
  0.155   0.160   0.160   0.160   0.160   0.160   0.160   0.160   0.155
  0.134   0.134   0.134   0.134   0.134   0.134   0.134   0.134   0.134
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
  900.00  950.00 1000.00 1030.00 1050.00 1040.00 1020.00 1000.00  950.0
  850.00  900.00  920.00  940.00  950.00  940.00  920.00  900.00  850.0
  760.00  800.00  820.00  840.00  850.00  840.00  820.00  800.00  760.0
  720.00  750.00  750.00  750.00  750.00  750.00  750.00  750.00  720.0
  630.00  650.00  650.00  650.00  650.00  650.00  650.00  650.00  630.0
  580.00  600.00  600.00  600.00  600.00  600.00  600.00  600.00  580.0
```

```
           (filename = DROP.DAT)
XPOLD  :     0.0451 YPOLD  :     0.0000
UPOLD  :     0.1020 VPOLD  :     9.1490
DINIT  : 0.311E-03 RNDNUM :     0.0000
L/D    :       2.37 LN(D/D):  100.0000
XPOLD  :     0.0451 YPOLD  :     0.0000
UPOLD  :     0.1030 VPOLD  :     7.3480
DINIT  : 0.311E-03 RNDNUM :     0.0000
L/D    :     976.00 LN(D/D):  100.0000
XPOLD  :     0.0450 YPOLD  :     0.0000
UPOLD  :     0.0940 VPOLD  :    10.1140
DINIT  : 0.381E-03 RNDNUM :     0.0000
L/D    :       2.21 LN(D/D):  100.0000
XPOLD  :     0.0450 YPOLD  :     0.0000
UPOLD  :     0.0950 VPOLD  :     8.2630
DINIT  : 0.381E-03 RNDNUM :     0.0000
L/D    :     926.00 LN(D/D):  100.0000
XPOLD  :     0.0450 YPOLD  :     0.0000
UPOLD  :     0.0990 VPOLD  :     9.1520
DINIT  : 0.264E-03 RNDNUM :     0.0000
L/D    :       2.94 LN(D/D):  100.0000
XPOLD  :     0.0451 YPOLD  :     0.0000
UPOLD  :     0.1000 VPOLD  :     7.2940
DINIT  : 0.264E-03 RNDNUM :     0.0000
L/D    :    1200.00 LN(D/D):  100.0000
```

```
          ASA 3 and FUEL OIL (80.20)
TINIT   :  298.0000
TBL1    :  403.0000 TBL2    :  523.0000 TBL3    :  800.0000
DRT2    :    0.1500 DRT3    :    0.0132 DRT4    :    0.0000
CPLIQ1  : 1720.00   CPLIQ2  : 1890.00   CPLIQ3  : 1920.00
LHELIQ1: 3.350E+05 LHELIQ2: 2.700E+05
RHOLIQ1:  870.00   RHOLIQ2:  880.00   RHOLIQ3: 1500.00
HCOMLQ1: 4.310E+07 HCOMLQ2: 4.230E+07
AFMRAT1:     3.135 AFMRAT2:     3.125 AFMRAT3:     1.333
TRNO    :   0.1000
NSTEP   :   5.0000 DSAFE   :    0.2000
TSAFE   :   0.2000 ESAFE   :    0.2000
TOL1    :   0.0001 NRAMP   :     15
MAXSTP  :     5000
NDROP   :   6
NPRT1   :   2
NPRT2   :  50
IOUT(1):   0
IOUT(2):   0
IOUT(3):   1
IOUT(4):   0
IOUT(5):   1
IOUT(6):   0
IOUT(7):           1
INPTYP1:   0
INPTYP2:   0
INPTYP3:   0
INPTYP4:   0
TWDUM   :  300.0   TGDUM   :  300.0
UDUM    :    0.0000 VDUM   :    0.0
```

```
        (filename:  DROP2D1.FOR
C                             2DFFDBM
C
C       2-DIMENSIONAL FLAT FLAME DROPLET BALLISTICS MODEL
C
C       THIS VERSION HAS THE EFFECT OF GRAVITY INCLUDED IN THE AXIAL
C       DIRECTION AND THE VELOCITY AS AN INPUT FOR MASS FLOW RATE.
C       ALSO THE SPACING BETWEEN  DROPLETS IS CONSIDERED IN THE DRAG
C       FORCE, AND SPACING DECREASES AS THE DROPLET SLOWS DOWN (TO
C       PRESERVE MASS FLUX).
C
C      MODIFIED BY MARK S. SHELDON FROM ORIGINAL CODE BY WYMAN CLARK
C                      ENERGY AND ENVIRONMENTAL RESEARCH CORPORATION
C                      18 MASON
C                      IRVINE, CALIFORNIA  92718
C                      (714) 859-8851
C      CURRENT VERSION DATED 7/85.
C
C      REMODIFIED BY SUSAN B. ROBINSON
C                      ENERGY AND ENVIRONMENTAL RESEARCH CORPORATION
C                      200 EASTOWNE DR., SUITE 203
C                      CHAPEL HILL, NC  27514
C                      (919) 489-1726
C      CURRENT VERSION DATED  4/87.
C
C      REMODIFIED BY JIM MULHOLLAND
C                    ENVIRONMENTAL PROTECTION AGENCY
C                    HIGHWAY 54 & ALEXANDER DR.
C                    RESEARCH TRIANGLE PARK, NC 27711
C                    919-541-7663
C      CURRENT VERSION DATED 6/2/87
C
C      PROGRAM 2DFFDBM
C
C      2DFFDBM IS THE MAIN PROGRAM FOR THE 2-DIMENSIONAL
C      HAZARDOUS WASTE INCINERATION MODEL.
C      HERE IT HAS BE MODIFIED TO ACT AS AN INPUT ROUTINE FOR THE
C      DROPLET EVAPORATION MODEL.
C
       REAL MDOTXP,MDOTXN,MDOTYP,MDOTYN
       LOGICAL*1 CASE(80)
C*****
C
C          ADDITIONAL DECLARATIONS NEEDED FOR INJECTION ROUTINE
C
       INTEGER RMAX,XMAX
       INTEGER RMAXP,XMAXP
       LOGICAL*1 INCASE
       PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
       COMMON/ZDIMCB/
     1         IX, IY, IXPLUS, IYPLUS
C
       COMMON/GASCB/
     1         CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2        ,FO2, FN2, FCO2, FH2O
```

```
101    FORMAT(8X,E10.3,9X,F10.4)
102    FORMAT(8X,F10.2,9X,F10.4)
C
       XPOLD = XPINIT
       YPOLD = YPINIT
C
       DINIT2 = 0.0
       DINIT3 = 0.0
       DINIT4 = 0.0
       IF(DRT2.EQ.0.0) GO TO 400
       DINIT2 = (((DINIT**3) * RHOLIQ1 * DRT2)/(RHOLIQ2 -
      1          RHOLIQ2*DRT2 + RHOLIQ1*DRT2))**(1./3.)
       IF(DRT3.EQ.0.0) GO TO 400
       DINIT3 = (((DINIT**3) * RHOLIQ1 * DRT3)/(RHOLIQ3 +
      1          DRT2*RHOLIQ1*RHOLIQ3/RHOLIQ2 + DRT3*RHOLIQ1 +
      2          DRT2*RHOLIQ3 + DRT3*RHOLIQ3))**(1./3.)
       DINIT2 = ((((DINIT3**3) * DRT2 * RHOLIQ3)/(DRT3*RHOLIQ2)) +
      1          (DINIT3**3))**(1./3.)
       DINIT4 = ((DINIT3**3)*(DRT4/DRT3))**(1./3.)
400    CONTINUE
C
         WRITE(6,500)DINIT,DINIT2,DINIT3,DINIT4,UPOLD,VPOLD,LDINIT
         WRITE(7,500)DINIT,DINIT2,DINIT3,DINIT4,UPOLD,VPOLD,LDINIT
         WRITE(2,500)DINIT,DINIT2,DINIT3,DINIT4,UPOLD,VPOLD,LDINIT
500      FORMAT(/ ' DROPLET INJECTION CONDITIONS:'/
      1          ' DINIT (M) = ',E10.3/ ' D2 (M) = ',E10.3,
      2          ' D3 (M) = ',E10.3,' D4 (M) = ',E10.3/
      3          ' VXINIT (M/S) = ',F10.4,' VYINIT (M/S) = ',F10.4/
      4          ' LINIT/DINIT = ',F10.2/)
C
C         CHANGE L/D TO SPACING
C
       SDINIT = LDINIT * DINIT
C
C         LOCATE INITIAL ZONE
C
       II = 1
       DO 200 I = 2, IXPLUS
          IF(XPOLD.LT.XBDY(I)) GOTO 210I = II + 1
200    CONTINUE
210    CONTINUE
       IF(II.GT.IX) II = IX
C
       JI = 1
       DO 300 J = 2, IYPLUS
          IF(YPOLD.LT.YBDY(J)) GOTO 310
          JI = JI + 1
300    CONTINUE
310    CONTINUE
       IF(JI.GT.IY) JI = IY
C      WRITE(2,320) II,JI
 320   FORMAT(2X,'II = ',I3,' JI = ',I3)
       SAVEII=II
       SAVEJI=JI
C
```

```
C
C         COMMON VARIABLES FROM SUBROUTINE SPRAY
C
      REAL LDINIT
C
      COMMON/INPUT/
     1         MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1        ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     2        ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/ZDIMCB/
     1         IX, IY, IXPLUS, IYPLUS
C
      COMMON/ZBDYCB/
     1         UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
     2        ,XBDY(XMAXP)  , YBDY(RMAXP)
     3        ,TWALL(XMAX,RMAX)
C
      COMMON/GASCB/
     1         CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2        ,FO2, FN2, FCO2, FH2O
C
      COMMON/LIQCB/
     1         TLIQ, TINIT, IDUM
     2       , TBOIL, TBL1, TBL2, TBL3
     3       , DRT2, DRT3, DRT4
     4       , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5       , LHELIQ, LHELIQ1, LHELIQ2
     6       , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7       , HCOMLQ, HCOMLQ1, HCOMLQ2
     8       , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/DROPCB/
     1         XPOLD, YPOLD, UPOLD, VPOLD, VINIT, SPACE, C, XPINIT
     2         , RNDNUM, SDINIT, JRAND, LDINIT, DPOLD, TPOLD
     3       , DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/PARMCB/
     1         NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2        ,MAXSTP, NRAMP, NDROP, TRNO
C
      COMMON/PRTCB/
     1         CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
      COMMON/SAVE/
     1         SAVEII,SAVEJI
C
C      INPUT FROM DATA FILE FOR NOW
C
      READ(4,100) XPINIT, YPINIT
      READ(4,100) UPOLD, VPOLD
      READ(4,101) DINIT, RNDNUM
      READ(4,102) LDINIT, C
 100  FORMAT(8X,F10.4,9X,F10.4)
```

```
C
700   CONTINUE
      DMASS =  (DIAM / DINIT)**3.
      IF(DMASS.GT.RNDNUM) GOTO 710
      DUM1 = DIAM*1.E6
      DPOLD = DUM1
      TPOLD = TLIQ
      DUM2 = 1. - DMASS
      IF (IOUT(3).EQ.1) WRITE(2,720)II,JI,COUNT2,TIME,XPOLD,YPOLD
     1          ,UPOLD,VPOLD,TLIQ,DUM1,DUM2
720   FORMAT(1X,I3,I3,I5,E10.3,F7.4,F7.4,2(F7.3),F7.1,F8.2,F8.3/)
      RETURN
C
C         IF NOT EVAPORATED, ENTER NEW ZONE
C
710   CONTINUE
      II = IINEW
      IF(JINEW.NE.0) GOTO 800
         VPOLD = -VPOLD
         JINEW = 1
800   CONTINUE
      JI = JINEW
C
C         IF TEMP OF NEW ZONE IS < TBOIL, RECALCULATE DROP TEMP
C
      IF(TEMP(II,JI).LT.TBOIL) BOIL = .FALSE.
C
1000  CONTINUE
C
C         IF ZONE LOOP COMPLETED WITHOUT EVAPORATION, SEND WARNING MESSAGE
C
      IF(IOUT(3).EQ.1) WRITE(2,900) MAXSTP
900   FORMAT(1X,'DROPLET NOT EVAPORATED AFTER ',I8,' ZONES VISITED')
      RETURN
      END
C ------------------------------------------------------------------
      SUBROUTINE SPRAYV
C     Written by Mark Sheldon, 4/18/85
C
C     PURPOSE:
C         SPRAY returns droplet initial conditions to DROP.
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP, MDOTXN, MDOTYP, MDOTYN
      LOGICAL*1 CASE(80)
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      REAL LHELIQ, LHELIQ1, LHELIQ2
      REAL NSTEP
      INTEGER RMAX,XMAX
      INTEGER RMAXP,XMAXP
      LOGICAL*1 INCASE
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
```

```
C
      TIME4 = 1.E20
      IF(.NOT.BOIL) TIME4 = CON2*TSAFE
C
      TIME5 = 1.E20
      IF(CBOIL.GE.0.) TIME5 = CON3*ESAFE
C
      DUM1 = TIME1
      IF(TIME2.LE.DUM1) DUM1 = TIME2
      IF(TIME3.LE.DUM1) DUM1 = TIME3
      IF(TIME4.LE.DUM1) DUM1 = TIME4
      IF(TIME5.LE.DUM1) DUM1 = TIME5
      IF(DUM1.LE.1.E+21) DTIME = DUM1
      DTSAV = DTIME
C
C         TIMESTSTEPS ACROSS ZONE
C
C
      DO 2000 COUNT2 = 1,MAXSTP
          CALL DPMVV
          IF(GETOUT) GOTO 600
C
C         CHECK FOR ZONE BOUNDARY
C         IF STILL IN ZONE, CONTINUE IN 'DO 2000' LOOP FOR NEXT TIMESTEP
C         IF ZONE BOUNDARY REACHED, GET OUT OF 'DO 2000' LOOP
C
      IF (IINEW.NE.II) GOTO 600
      IF (JINEW.NE.JI) GOTO 600
2000  CONTINUE
C
C         IF NOT OUT OF ZONE IN REASONABLE TIME,
C         DROPLET MAY BE OUT OF STEAM
C
      IF (IOUT(3).EQ.1) WRITE(2,620)MAXSTP,UPOLD,VPOLD
620   FORMAT(1X,/,1X,'STILL IN ZONE AFTER ',I7,' STEPS.'
     1      ,/,'  UPOLD = ',E10.3,' M/S, AND VPOLD = ',E10.3,' M/S'/)
      RETURN
C
C         END-OF-ZONE CALCULATIONS
C
600   CONTINUE
C
C         CHECK WHETHER ZONE BOUNDARY IS A SOLID WALL
C
      IF(IINEW.EQ.0) ENUF = .TRUE.
      IF(IINEW.EQ.IXPLUS) ENUF = .TRUE.
      IF(JINEW.EQ.IYPLUS) ENUF = .TRUE.
      IF(.NOT.ENUF) GOTO 700
C
      IF(BOIL.OR.TWALL(II,JI).GT.TBOIL) RETURN
      IF(IOUT(3).EQ.1) WRITE(2,610)
610   FORMAT(1X,'DROP CONDENSED ON COLD SURFACE, WILL NOT BOIL')
      RETURN
C
C         CHECK FOR EVAPORATION IN PAST ZONE
```

```
      IF(RENOLD.GE.1.E4) CDINF = 2.
C
C
C         ADJUST DRAG COEFFICIENT FOR CLOSELY SPACED DROPLETS
C
      VDMAG = SQRT( UPOLD**2 + VPOLD**2 )
      SPACE = VDMAG * SDINIT / VINIT
      IF (SPACE.LT.DIAM) SPACE = DIAM
      D1 = ALOG(SPACE/DINIT)
      CD2 = 0.755/RENOLD + 34.8 * RENOLD**(-1.009) * (SPACE/DIAM-1.)
      EXP1= -1. /.7072
      CD = (CDINF ** (-0.7072) + CD2 ** (-0.7072)) ** EXP1
C
      IF(IOUT(4).EQ.4) CD = CDINF
C
C         ETAE ACCOUNTS FOR EFFECT OF MASS TRANSFER (EVAP) ON DRAG
C
      ETAE = 1.
      IF(BOIL) ETAE  = 1. / ( 1. + TRANSNO )
C
      IF(IOUT(4).EQ.7) ETAE = 1.0
C
      CDINF = CDINF * ETAE
      CD    = CD * ETAE
      CDRE  = CD * RENOLD
C
      CON1 = -1.
      IF(CDRE.GT.1.E-10)
     1        CON1 = 1./( 0.75 * DVISCG(II,JI) / RHOLIQ / DIAM / DIAM
     2        * CDRE )
C
      PRANDT = CPGAS(II,JI) * DVISCG(II,JI) / TCONDG(II,JI)
      NUSELT = 2. + 0.6 * (RENOLD**0.5) * (PRANDT**(1./3.))
      CON2 = RHOLIQ * DIAM * DIAM * CPLIQ / 6. / NUSELT / TCONDG(II,JI)
C
      CBOIL = -1.
      IF(TEMP(II,JI).GE.TLIQ) CBOIL =
     1      8. * TCONDG(II,JI) / RHOLIQ / CPGAS(II,JI)
     2      *ALOG(1. + TRANSNO)
      CON3 = DIAM*DIAM/CBOIL/(1. + 0.23*(RENOLD**0.5))
C
C         TIMESTEP SIZE
C
      OLDDT = DTIME
C
      TIME1 = 1.E20
      IF(UPOLD.GT.+1.E-7) TIME1 = (XBDY(II+1) - XPOLD) /UPOLD /NSTEP
      IF(UPOLD.LT.-1.E-7) TIME1 = (XBDY(II)   - XPOLD) /UPOLD /NSTEP
C
      TIME2 = 1.E20
      IF(VPOLD.GT.+1.E-7) TIME2 = (YBDY(JI+1) - YPOLD) /VPOLD /NSTEP
      IF(VPOLD.LT.-1.E-7) TIME2 = (YBDY(JI)   - YPOLD) /VPOLD /NSTEP
C
      TIME3 = 1.E20
      IF(CON1.GE.0.) TIME3 = CON1*DSAFE
```

```
C
30    BOIL   = .FALSE.
      IF(TLIQ.GE.TBOIL) BOIL = .TRUE.
      IF(TLIQ.GT.TBOIL.AND.IOUT(3).EQ.1) WRITE(2,50)
50    FORMAT(1X,'SUPERHEATED DROPLET')
      CNVRG  = .FALSE.
      GETOUT = .FALSE.
      ENUF   = .FALSE.
      IINEW  = II
      JINEW  = JI
      DIAM   = DINIT
      TIME   = 0.0
      DT     = 0.0
      DTIME  = 1.0E-5
      START1 = 0.
      START2 = 0.
C
C         INITIALIZE GAS VELOCITY
C
      UGAS = UBDY(II,JI) + (UBDY(II+1,JI) - UBDY(II,JI))
     1                    *(XPOLD - XBDY(II)) / (XBDY(II+1) - XBDY(II))
C
      VGAS = VBDY(II,JI) + (VBDY(II,JI+1) - VBDY(II,JI))
     1                    *(YPOLD - YBDY(JI)) / (YBDY(JI+1) - YBDY(JI))
C
      VINIT = SQRT( (UPOLD-UGAS)**2 + (VPOLD-VGAS)**2 )
C
C         ZONE CALCULATIONS
C            (ARBITRARY SAFETY LIMIT SET ON NUMBER OF ZONE PASSES)
C
      DO 1000 COUNT1 = 1,MAXSTP
C
C         CONSTANTS FOR TIMESTEP CALCULATION
C
      VMAG = SQRT( (UPOLD-UGAS)**2 + (VPOLD-VGAS)**2 )
      IF(IOUT(6).NE.1) GOTO 99
          DUM1 = ATAN2(VPOLD,UPOLD)
          DUM2 = ATAN2(VGAS,UGAS) - DUM1
          DUM3 = SQRT( UGAS**2 + VGAS**2 )
          VMAG = ABS( DUM3 * SIN(DUM2) )
 99   CONTINUE
C
      RENOLD = DIAM * DENS(SUMASS,TEMP(II,JI)) * VMAG / DVISCG(II,JI)
      IF(IDUM.EQ.2) GO TO 200
      TRANSNO = (CPGAS(II,JI) * (TEMP(II,JI)-TLIQ) +
     1             HCOMLQ * FO2 / AFMRAT) / LHELIQ
      GO TO 210
 200  CONTINUE
      IF(IOUT(7).EQ.0) TRANSNO = FO2 / AFMRAT
      IF(IOUT(7).EQ.1) TRANSNO = TRNO
 210  CONTINUE
C
      IF(RENOLD.LE.80) CDINF = 27. * RENOLD**(-0.84)
      IF(RENOLD.GT.80.AND.RENOLD.LT.1.E4)
     1          CDINF = 0.271 * RENOLD**(0.217)
     1          MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1         ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     2         ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/ZDIMCB/
     1          IX, IY, IXPLUS, IYPLUS
C
      COMMON/ZBDYCB/
     1          UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
     2         ,XBDY(XMAXP)   , YBDY(RMAXP)
     3         ,TWALL(XMAX,RMAX)
C
      COMMON/GASCB/
     1          CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2         ,FO2, FN2, FCO2, FH2O
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/DROPCB/
     1          XPOLD, YPOLD, UPOLD, VPOLD, VINIT, SPACE, C, XPINIT
     2          , RNDNUM, SDINIT, JRAND, LDINIT, DPOLD, TPOLD
     3        , DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/PARMCB/
     1          NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2         ,MAXSTP, NRAMP, NDROP, TRNO
C
      COMMON/PRTCB/
     1          CASE, INCASE(80), IOUT(10)
     2          ,NPRT1, NPRT2
C
      COMMON/SAVE/
     1          SAVEII,SAVEJI
C
C       DENSITY (KG M**-3), IDEAL GAS AT 1 ATM
C             (SUMASS IS GMOLES PER KG OF GAS MIXTURE)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
      CALL SPRAYV
C
C          DROPLET INITIAL CONDITIONS
C
        II = SAVEII
        JI = SAVEJI
C
C          INITIALIZATIONS
```

```
C
1000  CONTINUE
C
C           OPTIONAL OUTPUT
C
      IF(IOUT(1).EQ.1) CALL GASPRTV
C
      RETURN
      END
C -------------------------------------------------------------------------
      SUBROUTINE DROPV
C
C     Written by Mark Sheldon for EER, 4/85
C
C     PURPOSE:
C         Return statistical evaporation zone of single liquid droplet.
C         Axisymmetric cylindrical coordinates.
C
C         LOCAL VARIABLES
C
      REAL NUSELT
      LOGICAL ENUF
C
C         COMMON VARIABLES SET IN SUBROUTINE DROP (AND DRPMOV)
C
      INTEGER COUNT1, COUNT2, DSTMAX
      LOGICAL BOIL, CNVRG, GETOUT
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP, MDOTXN, MDOTYP, MDOTYN
      INTEGER RMAX,XMAX ,RMAXP,XMAXP
      LOGICAL*1 CASE(80)
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      REAL LHELIQ, LHELIQ1, LHELIQ2
      REAL NSTEP
      INTEGER START1
      INTEGER START2
      LOGICAL*1 INCASE
C
C         COMMON VARIABLES FROM SUBROUTINE SPRAY
C
      REAL LDINIT
C
      COMMON/MOVECB/
     1          DTIME, DTSAV, OLDDT, TIME
     2         ,DIAM,  UGAS , VGAS , PRANDT
     3         ,IINEW, JINEW, COUNT1, COUNT2
     4         ,BOIL , CNVRG, GETOUT, DT, START1, START2
C
      COMMON/INPUT/
```

```
C
      IF(IPOLAR(L).EQ.0) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1        * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.70 / TDUM2) + 0.9168 )
     3        * KFUDGE(L)
C
      IF(IPOLAR(L).EQ.1) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1        * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.69 / TDUM2) + 1.077
     3           - (3. * KALPH(L)) - (0.3 * KCIR(L))  )
     4        * KFUDGE(L)
C
2000  CONTINUE
C
C         LOOP FOR MIXTURE WEIGHTING FUNCTIONS
C
      DO 3000 L = 1, NGSPEC
      VWGT(L) = 0.
      KWGT(L) = 0.
      DO 3000 M = 1, NGSPEC
C
C         VISCOSITY WEIGHTING FUNCTION
C
      DUM2 = 1.0
      IF((DELTA(L).GE.0.1).OR.(DELTA(M).GE.0.1))
     1    DUM2 = ( 1. + SQRT( (TEMP(I,J)/EPS(L)) * (TEMP(I,J)/EPS(M)) )
     2                + DELTA(L) * DELTA(M) * 0.25 )
     3          /SQRT( 1. + TEMP(I,J)/EPS(L) + DELTA(L)*DELTA(L)*0.25 )
     4          /SQRT( 1. + TEMP(I,J)/EPS(M) + DELTA(M)*DELTA(M)*0.25 )
C
      DUM3 = DUM2 * VAFUN(L,M) * SQRT( VISC(L)/VISC(M) )
C
      VWGT(L) = VWGT(L) + DUM3 * MOLEFR(M)
C
C         THERMAL CONDUCTIVITY WEIGHTING FUNCTION
C
      DUM4 = ( 1. + SQRT( VISC(L)/VISC(M) )
     1                 *( MOLWT(M)/MOLWT(L) )**0.25 )**2.
     2        / SQRT( 8. * (1. + MOLWT(L)/MOLWT(M) ) )
C
      KWGT(L) = KWGT(L) + DUM4 * MOLEFR(M)
C
3000  CONTINUE
C
C         MIXTURE PROPERTIES
C
      CPGAS(I,J)  = 0.0
      DVISCG(I,J) = 0.0
      TCONDG(I,J) = 0.0
C
      DO 4000 L = 1, NGSPEC
         CPGAS(I,J)  = CPGAS(I,J)  + CP(L)   * MASSFR(L)
         DVISCG(I,J) = DVISCG(I,J) + VISC(L) * MOLEFR(L) / VWGT(L)
         TCONDG(I,J) = TCONDG(I,J) + COND(L) * MOLEFR(L) / KWGT(L)
4000  CONTINUE
```

```
C         LOOP FOR PURE COMPONENT PROPERTIES
C
      DO 2000 L = 1, NGSPEC
C
C         PURE COMPONENT HEAT CAPACITY
C
      TDUM1 = TEMP(I,J)*1.8
C
      IF(TDUM1.LT.540.) WRITE(2,410) TDUM1
410   FORMAT(1X,'***WARNING: GAS TEMP=',F8.1,/,1X
     1           ,'FARENHEIT, TOO LOW  FOR EMPIRICAL CP EQNS. IN GPROP')
      IF(TDUM1.GT.5000.)WRITE(2,420) TDUM1
420   FORMAT(1X,'***WARNING: GAS TEMP=',F8.1,/,1X
     2           ,'FARENHEIT, TOO HIGH FOR EMPIRICAL CP EQNS. IN GPROP')
C
      IF(L.EQ.1) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 11.515 - 172.*( TDUM1**(-0.5) ) + 1530./TDUM1 )
C
      IF(L.EQ.2) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * (    9.47  - 3.47E3 / TDUM1                + 1.16E6/TDUM1/TDUM1 )
C
      IF(L.EQ.3) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 16.2   - 6.53E3 / TDUM1                  + 1.41E6/TDUM1/TDUM1 )
C
      IF(L.EQ.4) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 19.86  - 597.*( TDUM1**(-0.5) ) + 7500./TDUM1 )
C
C         PURE COMPONENT VISCOSITY
C         (DUM1 IS THE INTEGRAL 'OMEGA' BASED ON STOCKMEYER POTENTIAl)
C
      TDUM1 = TEMP(I,J)/EPS(L)
C
      IF(TDUM1.LT.0.3) WRITE(2,430) TDUM1, L, I, J
430   FORMAT(1X,'WARNING: NONDIMEN TEMP = ',F6.2
     1           ,' FOR SPECIES L=',I3,'T ZONE I=',I3,', J=',I3,/
     2         1X,9X,'TOO LOW FOR ACCURATE VISCOSITY PREDICTION')
C
      IF(TDUM1.GT.100.) WRITE(2,440) TDUM1, L, I, J
440   FORMAT(1X,'WARNING: NONDIMEN TEMP = ',F6.2
     1           ,' FOR SPECIES L=',I3,' AT ZONE I=',I3,', J=',I3,/
     2         1X,9X,'TOO HIGH FOR ACCURATE VISCOSITY PREDICTION')
C
      DUM1  =  1.16145 / (TDUM1**0.14874)
     1         + 0.52487 * EXP(-0.77320*TDUM1)
     2         + 2.16178 * EXP(-2.43787*TDUM1)
     3         + 0.2 * DELTA(L) * DELTA(L) / TDUM1
C
      VISC(L) = (26.69E-7 * SQRT( MOLWT(L)*TEMP(I,J) )
     1            / SIGMA(L) / SIGMA(L) / DUM1)
     2            * VFUDGE(L)
C
C         PURE COMPONENT THERMAL CONDUCTIVITY
C         (EQUATION HAS 2 FORMS, FOR NONPOLAR AND POLAR SPECIES)
C
      TDUM2 = TEMP(I,J)/TCRIT(L)
      DATA VFUDGE/ 1.0          , 1.0     , 1.0     , 1.0 /
      DATA KFUDGE/ 1.0          , 1.0     , 1.0     , 1.0 /
      DATA CFUDGE/ 1.0          , 1.0     , 1.0     , 1.0 /
C
C         TEMPERATURE-INDEPENDENT CALCULATIONS
C
C         MASS FRACTIONS
C
      MASSFR(1) = F02
      MASSFR(2) = FN2
      MASSFR(3) = FC02
      MASSFR(4) = FH20
C
C         CHECK MASSFR NORMALIZATION
C
      DUM1 = -1.
      DO 210 L = 1,NGSPEC
          DUM1 = MASSFR(L) + DUM1
210    CONTINUE
      IF(DUM1.LT.-1.E-6) WRITE(2,220) DUM1
220   FORMAT(1X,'***WARNING: SUM OF MASS FRACTIONS IS '
     1            ,E10.3,' BELOW 1')
      IF(DUM1.GT.+1.E-6) WRITE(2,230) DUM1
230   FORMAT(1X,'***WARNING: SUM OF MASS FRACTIONS IS '
     1            ,E10.3,' ABOVE 1')
C
C         MOLE FRACTIONS
C
      DUM1 = 0.
      DO 310 L = 1, NGSPEC
          DUM1 = DUM1 + MASSFR(L)/MOLWT(L)
310   CONTINUE
      DO 320 L = 1, NGSPEC
C
      MOLEFR(L) = (MASSFR(L)/MOLWT(L) ) / DUM1
320   CONTINUE
C
C         TEMPERATURE INDEPENDENT WEIGHTING FUNCTION (A) FOR MIX VISCOSITY
C
      DO 330 M = 1, NGSPEC
      DO 330 L = 1, NGSPEC
          DUM1 = MOLWT(L) / MOLWT(M)
          DUM2 = ( 4./ (1. + 1./DUM1) / (1. + DUM1) )**0.25
       DUM3 = DUM2 * (DUM1**(-0.5))
          DUM4 = DUM1 - (DUM1**(0.45))
          DUM5 = 2. * (1. + DUM1)
          DUM6 = (1. + (DUM1**(0.45)) ) * (DUM2**(-0.5))
          DUM7 = 1. + DUM2
          VAFUN(L,M) = DUM3 * (1. + DUM4/ (DUM5 + DUM6/DUM7) )
330   CONTINUE
C         LOOP THROUGH ALL ZONES I,J
C
      DO 1000 J = 1, IY
      DO 1000 I = 1, IX
C
```

```
      LOGICAL*1 CASE(80)
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      LOGICAL*1 INCASE
C
C         COMMON VARIABLES FROM SUBROUTINE GPROP
C
C
      COMMON/INPUT/
     1         MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1        ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     2        ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/ZDIMCB/
     1         IX, IY, IXPLUS, IYPLUS
C
      COMMON/GASCB/
     1         CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2        ,FO2, FN2, FCO2, FH2O
C
      COMMON/PRTCB/
     1         CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
C          MOLECULAR PARAMETERS
C
C          NUMBER OF GAS SPECIES
       DATA NGSPEC/4/
C
C          MOLECULAR WEIGHTS (G/GMOLE)
       DATA MOLWT /32.00   , 28.02   , 44.01   , 18.02     /
C
C          LENNARD-JONES (AND STOCKMEYER) PARAMETERS
C          (SIGMA IN ANGSTROMS, EPS IN KELVIN)
       DATA SIGMA /3.433   , 3.681   , 3.996   , 2.52      /
       DATA EPS     /113.      , 91.5    , 190.     , 775. /
       DATA DELTA /0.0          , 0.0     , 0.0      , 1.0  /
C
C          CRITICAL TEMPERATURES (KELVIN)
       DATA TCRIT /154.8    , 126.2    , 304.2    , 647.3     /
C
C          PARAMETERS FOR POLAR VERSION OF THERMAL CONDUCTIVITY
C          (IPOLAR IS FLAG: =0 IF NONPOLAR, =1 IF POLAR)
C          (ALPHA AND CIR HAVE UNITS OF CAL/GMOLE/KELVIN)
       DATA IPOLAR/  0,           0,          0,         1/
       DATA KALPH / 0.0         , 0.0      , 0.0      , 0.90 /
       DATA KCIR  / 0.0         , 0.0      , 0.0      , 0.0  /
C
C          FUDGE FACTORS ARE RATIOS OF EXPERIMENTAL TO CALCULATED VALUES
C          AT REFERENCE TEMPERATURE (1300 K UNLESS OTHERWISE NOTED)
C
C          NOTE: BEGIN BY USING FUDGE FACTORS SET TO 1.0
C
```

```
      DO 770 I=1.IX
          IF(VBDY(I,1).GT.1.E-6)L=1
770   CONTINUE
      IF(L.EQ.1) WRITE(2,780)
780   FORMAT(1X,'***WARNING: FLOW ACROSS CENTERLINE NONZERO'
     1            ,' SEE SETINJ')
C
C         WALL TEMPERATURES (HARDCODED FOR NOW)
C
      IF(INPTYP(1).EQ.1)GOTO 810
          DO 820 J=1,IY
          DO 820 I=1,IX
            TWALL(I,J) = TEMP(I,J)
820       CONTINUE
810   CONTINUE
C
C         OPTIONAL OUTPUT
C
      IF(IOUT(2).EQ.1) CALL SETPRT
C
      RETURN
      END
C --------------------------------------------------------------------
      SUBROUTINE GPROPV
C
C     Written by Mark Sheldon for EER, 4/16/85
C
C     PURPOSE:
C         GPROP (Gas PROPerties) calculates the heat capacity, viscosity,
C         and thermal conductivity of an ideal gas mixture including:
C
C         No.  Formula            Name
C          1     02 Diatomic Oxygen
C          2     N2 Diatomic Nitrogen
C          3     C02          Carbon Dioxide
C          4     H20          Water Vapor
C
C         Primary Reference:
C            Reid, Prausnitz and Sherwood  (1977)
C            The Properties of Gases and Liquids, 3rd ed.
C
C         LOCAL VARIABLES
C
      REAL CP(4)     , VISC(4)  , COND(4)
     1        ,MASSFR(4) , MOLEFR(4), MOLWT(4)
     2        ,SIGMA(4)  , EPS(4)   , DELTA(4)
     3        ,TCRIT(4)  , KALPH(4) , KCIR(4)
     4        ,VAFUN(4,4), VWGT(4)  , KWGT(4)
     5        ,VFUDGE(4) , CFUDGE(4), KFUDGE(4)
      INTEGER IPOLAR(4)
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP, MDOTXM, MDOTYP, MDOTYM
      INTEGER RMAX,XMAX,RMAXP,XMAXP
```

```
420         CONTINUE
410   CONTINUE
C
      IF(INPTYP(2).EQ.0)GOTO 430
          DO 440 J=1,IY
          DO 440 I=1,IX
            TEMP(I,J) = TGDUM
440       CONTINUE
430   CONTINUE
C
      IF(INPTYP(3).EQ.0)GOTO 450
          DO 460 J=1,IY
          DO 460 I=1,IXPLUS
            UBDY(I,J) = UDUM
460       CONTINUE
450   CONTINUE
C
      IF(INPTYP(4).EQ.0)GOTO 470
          DO 480 J=1,IYPLUS
          DO 480 I=1,IX
            VBDY(I,J) = VDUM
 480       CONTINUE
470   CONTINUE
C
C         COORDINATES OF ZONE BOUNDARIES
C
      XBDY(1) = 0.
      DO 600 I = 1,IX
          XBDY(I+1) = XBDY(I) + XL(I)
600   CONTINUE
C
      YBDY(1) = 0.
      DO 650 J = 1, IY
          YBDY(J+1) = R(J)
650   CONTINUE
C
C         AREAS AND VELOCITIES AT ZONE BOUNDARIES
C
      IF(INPTYP(3).EQ.1)GOTO 710
      DO 740 I = 1,IXPLUS
          SUMMDOT=0.
          DO 720 J = 1,IY
            XAREA = PI * (YBDY(J+1)*YBDY(J+1)-YBDY(J)*YBDY(J))
            IF(I.EQ.1) DUM1 = TEMP(I,J)
            IF(I.NE.1.AND.I.NE.IXPLUS)
     1         DUM1 = (TEMP(I,J) + TEMP(I-1,J)) * 0.5
            IF(I.EQ.IXPLUS) DUM1 = TEMP(I-1,J)
            XRHO = DENS(SUMASS,DUM1)
            MDOTXP(I,J)=XRHO*XAREA*UBDY(I,J)
            SUMMDOT=SUMMDOT+MDOTXP(I,J)
720       CONTINUE
740   CONTINUE
710   CONTINUE
C
      L = 0
```

```
310   FORMAT(8X,F10.4,9X,F10.4)
C
      CLOSE(UNIT=3)
C
C     WRITE MODEL RUN CONDITIONS TO SCREEN AND RESULT FILES
C
      WRITE(6,100) DRT2,DRT3,DRT4
      WRITE(2,100) DRT2,DRT3,DRT4
      WRITE(7,100) DRT2,DRT3,DRT4
100   FORMAT(2X,'MODEL RUN PARAMETERS:'/
     1        4X,'DRT2 = ',F10.4,2X,'DRT3 = ',F10.4,2X,'DRT4 = ',F10.4)
C
      IF(IOUT(7).EQ.1) WRITE(6,105) TRNO
      IF(IOUT(7).EQ.1) WRITE(2,105) TRNO
      IF(IOUT(7).EQ.1) WRITE(7,105) TRNO
105   FORMAT(2X,'PHASE 3 TRANSFER NUMBER = ',F10.6)
C
      IF(IOUT(4).EQ.1) WRITE(6,110)
      IF(IOUT(4).EQ.1) WRITE(2,110)
      IF(IOUT(4).EQ.1) WRITE(7,110)
110   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: GRAVITY = 0')
      IF(IOUT(4).EQ.2) WRITE(6,120)
      IF(IOUT(4).EQ.2) WRITE(2,120)
      IF(IOUT(4).EQ.2) WRITE(7,120)
120   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: DRAG = 0')
      IF(IOUT(4).EQ.3) WRITE(6,130)
      IF(IOUT(4).EQ.3) WRITE(2,130)
      IF(IOUT(4).EQ.3) WRITE(7,130)
130   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: GRAVITY = 0 AND DRAG = 0')
      IF(IOUT(4).EQ.4) WRITE(6,140)
      IF(IOUT(4).EQ.4) WRITE(2,140)
      IF(IOUT(4).EQ.4) WRITE(7,140)
140   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: CD = CDINF')
      IF(IOUT(4).EQ.5) WRITE(6,150)
      IF(IOUT(4).EQ.5) WRITE(2,150)
      IF(IOUT(4).EQ.5) WRITE(7,150)
150   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: Q = 0')
      IF(IOUT(4).EQ.6) WRITE(6,160)
      IF(IOUT(4).EQ.6) WRITE(2,160)
      IF(IOUT(4).EQ.6) WRITE(7,160)
160   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: ETAS = 0')
      IF(IOUT(4).EQ.7) WRITE(6,170)
      IF(IOUT(4).EQ.7) WRITE(2,170)
      IF(IOUT(4).EQ.7) WRITE(7,170)
170   FORMAT(4X,'SPECIAL MODEL CONSTRAINT: ETAE = 0')
C
      IF(IOUT(4).EQ.5)HCOMLQ1 = 0.0
      IF(IOUT(4).EQ.5)HCOMLQ2 = 0.0
C
C         DUMMY INPUT OPTIONS
C
      IF(INPTYP(1).EQ.0)GOTO 410
          DO 420 J=1,IY
          DO 420 I=1,IX
            TWALL(I,J) = TWDUM
      READ(3,242)HCOMLQ1,HCOMLQ2
242   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(3,244)AFMRAT1,AFMRAT2,AFMRAT3
244   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(3,246)TRNO
246   FORMAT(8X,F10.6)
C
      READ(3,250)MSTEP,DSAFE
250   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(3,260)TSAFE,ESAFE
260   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(3,270)TOL1,NRAMP
270   FORMAT(8X,F10.4,9X,I10)
C
      READ(3,280)MAXSTP,NDROP
280   FORMAT(8X,I10/9X,I10)
C
      READ(3,290)NPRT1,NPRT2
 290  FORMAT(8X,I10/9X,I10)
C
C         USE OF ARRAY IOUT
C           IOUT INTENDED FOR USE AS OUTPUT SWITCH
C           IN SOME CASES USED TO AFFECT CALCULATION WHEN
C           OTHER METHODS ARE TOO PAINFUL OR QUICK WORK
C
C      CURRENTLY (ACTION IF IOUT=1... OPPOSITE IF IOUT=0)
C           IOUT(1) TURNS ON GASPRTV
C           IOUT(2) TURNS ON SETPRT
C           IOUT(3) TURNS ON DRPPRT
C           IOUT(4) TURNS ON OPTIONS
C           IOUT(5) TURNS ON GRAVITY IN +X DIRECTION
C           IOUT(6) TURNS ON GRAVITY IN +Y DIRECTION
C         IOUT(7) CHOOSES PHASE 3 TRANSFER NUMBER
C
C         INPTYP, HOWEVER, IS A LOCAL SWITCH FOR SETINJ
C           INPTYP(1) GIVES DUMMY TWALL
C           INPTYP(2) GIVES DUMMY TEMP
C           INPTYP(3) GIVES DUMMY UBDY
C           INPTYP(4) GIVES DUMMY VBDY
C
      READ(3,300)IOUT(1),IOUT(2)
      READ(3,300)IOUT(3),IOUT(4)
      READ(3,300)IOUT(5),IOUT(6)
      READ(3,305)IOUT(7)
305   FORMAT(8X,I10)
      READ(3,300)INPTYP(1),INPTYP(2)
      READ(3,300)INPTYP(3),INPTYP(4)
 300  FORMAT(8X,I10/8X,I10)
C
      READ(3,310) TWDUM,TGDUM
      READ(3,310) UDUM,VDUM
```

```
     2         ,XBDY(XMAXP) , YBDY(RMAXP)
     3         ,TWALL(XMAX,RMAX)
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1          NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2         ,MAXSTP, NRAMP, NDROP, TRNO
C
      COMMON/PRTCB/
     1          CASE, INCASE(80), IOUT(10)
     2          ,NPRT1, NPRT2
C
C         DENSITY (KG M**-3), IDEAL GAS AT 1 ATM.
C         (SUMASS IS GMOLES OF GAS PER KG OF GAS)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
C         INITIALIZE CONSTANT PARAMETERS
C
      PI = 3.14159
C
C         INPUT FROM DATA FILE
C
      OPEN(UNIT=3,STATUS='UNKNOWN',FILE='INJECT.DAT')
C
      READ(3,210)(INCASE(I),I=1,70)
210   FORMAT(70A1)
C
      READ(3,220)TINIT
220   FORMAT(8X,F10.4)
C
      READ(3,225)TBL1,TBL2,TBL3
225   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(3,226)DRT2,DRT3,DRT4
226   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(3,230)CPLIQ1,CPLIQ2,CPLIQ3
230   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(3,235)LHELIQ1,LHELIQ2
235   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(3,240)RHOLIQ1,RHOLIQ2,RHOLIQ3
240   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
```

```
        CPLIQ = CPLIQ1
        LHELIQ = LHELIQ1
        RHOLIQ = RHOLIQ1
        HCOMLQ = HCOMLQ1
        AFMRAT = AFMRAT1
          CALL DROPV
        XPOLD = 100 * (XPOLD - XPINIT)
        YPOLD = 100 * YPOLD
        WRITE(7,200) XPOLD,YPOLD,DPOLD,TPOLD,TIME
        WRITE(6,200) XPOLD,YPOLD,DPOLD,TPOLD,TIME
        WRITE(2,200) XPOLD,YPOLD,DPOLD,TPOLD,TIME
200     FORMAT(/ 3X,'X-ENDPOINT (CM) = ',F6.2,'  Y-ENDPOINT (CM) = ',
     1    F6.2/ 3X,'DIAMETER (uM) = ',F6.1,'  TEMPERATURE (K) = ',
     2    F7.1,'  TIME (SEC) = ',E10.3/)
1000  CONTINUE
C
      RETURN
      END
C --------------------------------------------------------------------
             SUBROUTINE      SETINJV
C
C         Written by Mark Sheldon for EER, 4/18/85
C     Modified by Susan Robinson for EER, 1/86
C
C     PURPOSE:
C         SETINJ (SETup for INJection) calculates initial data
C         for injection calculation (except gas properties).
C
      INTEGER INPTYP(4)
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP,MDXN, MDOTYP, MDOTYN
      LOGICAL*1 CASE(80)
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      REAL LHELIQ, LHELIQ1, LHELIQ2
      REAL NSTEP
      INTEGER RMAX,XMAX,RMAXP,XMAXP
      LOGICAL*1 INCASE
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
C         COMMON VARIABLES FROM DROP AND SPRAY
C
      COMMON/INPUT/
     1         MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1        ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     1        ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/ZDIMCB/
     1         IX, IY, IXPLUS, IYPLUS
C
      COMMON/ZBDYCB/
     1         UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
```

```
C
C          COMMON VARIABLES FROM SUBROUTINE SPRAY
C
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
      COMMON/INPUT/
     1         MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1         ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     1         ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/DROPCB/
     1          XPOLD, YPOLD, UPOLD, VPOLD, VINIT, SPACE, C, XPINIT
     2          , RNDNUM, SDINIT, JRAND, LDINIT, DPOLD, TPOLD
     3        , DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/PARMCB/
     1          NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2         ,MAXSTP, NRAMP, NDROP, TRNO
C
      COMMON/PRTCB/
     1          CASE, INCASE(80), IOUT(10)
     2          ,NPRT1, NPRT2
C
      COMMON/MOVECB/
     1          DTIME, DTSAV, OLDDT, TIME
     2         ,DIAM,  UGAS , VGAS , PRANDT
     3         ,IINEW, JINEW, COUNT1, COUNT2
     4         ,BOIL , CNVRG, GETOUT, DT, START1, START2
C
C          SET INCINERATOR CONDITIONS
C
      CALL SETINJV
      CALL GPROPV
C
C          INJECT DROPS AND TALLY THE INJECTION DISTRIBUTION
C
      DO 1000 I = 1, NDROP
        WRITE(6,100) I
        WRITE(7,100) I
        WRITE(2,100) I
100     FORMAT(// 1X,'DROP NO. ',I3,2X,'***************************'
     1          ,'*******************'/)
        IDUM = 0
          TLIQ = TINIT
        TBOIL = TBL1
      READ(1,20)(UBDY(I,J),J=1,IY)
 20   FORMAT(10F8.4)
 30   CONTINUE
      IYPLUS=IY+1
      DO 60 J=1,IYPLUS
      READ(1,20)(VBDY(I,J),I=1,IX)
 60   CONTINUE
C
      DO 80 I=1,IX
      READ(1,70)(TEMP(I,J),J=1,IY)
 70   FORMAT(10F8.2)
 80   CONTINUE
C
      CALL INJECTV
999   CONTINUE
      CLOSE(UNIT=7)
      CLOSE(UNIT=4)
      CLOSE(UNIT=2)
      CLOSE(UNIT=1)
C
      STOP
      END
C ---------------------------------------------------------------------
      SUBROUTINE INJECTV
C
C     Written by Mark Sheldon for EER, 4/17/85
C
C     PURPOSE:
C         INJECT is the main subroutine for the hazardous waste
C         injection model.  It returns the distribution of gas-phase
C         waste as it is injected into the combustor.  The overall
C         injection model is a statistical approach based on the droplet
C         trajectory/heating/evaporation model of Ayers,et.al.(1980)
C
C     SUBROUTINES CALLED BY INJECTV     (SOME INDIRECTLY):
C         SETINJV  Calculates data (except gas prop) for other routines
C         GPROPV   Calculates gas properties ( Cp, Visc, Therm. Cond.)
C         DROPV    Sends droplet through incinerator, zone by zone
C         SPRAYV   Gives initial conditions to each droplet
C         DPMVV    Trajectory/heating/evaporation of drop in 1 timestep
C         SETPRT     Output header from SETINJ
C         GASPRTV  Output header from GPROP
C         DRPPRT     Output header from DROP and/or SPRAY
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP, MDOTXN, MDOTYP, MDOTYN
      LOGICAL*1 CASE(80)
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      REAL  NSTEP, LHELIQ, LHELIQ1, LHELIQ2
      INTEGER RMAX,XMAX
      INTEGER RMAXP,XMAXP
      LOGICAL*1 INCASE
```

```
C
      COMMON/PRTCB/
     1          CASE, INCASE(80), IOUT(10)
     2          ,NPRT1, NPRT2
C
      COMMON/ZBDYCB/
     1          UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
     2         ,XBDY(XMAXP)  , YBDY(RMAXP)
     3         ,TWALL(XMAX,RMAX)
C
C
C   **ADDITIONAL CHANGES MADE**
C          -- OUTPUT OF DROPCIN SUPPRESSED WITH IOUTPT = 0
C          -- IF(IOUTPT(1).EQ.1) ADDED BEFORE HEADER PRINTING
C
C*****
      COMMON/INPUT/MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1       ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP), SUMASS
     2       ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/OUTPUT/IOUTPT(8)
C
      OPEN(UNIT=1,STATUS='OLD',FILE='FLOWF.DAT')
      OPEN(UNIT=2,STATUS='UNKNOWN',FILE='FULL2D.RES')
      OPEN(UNIT=4,STATUS='UNKNOWN',FILE='DROP.DAT')
      OPEN(UNIT=7,STATUS='UNKNOWN',FILE='SUM2D.RES')
C
C       INPUT TEST CONDITIONS:
C                                       CASE NAME,CASE
C                                       NUMBER OF AXIAL,RADIAL ZONES,IX,IY
C                                       ZONE RADII,R
C                                       ZONE LENGTH,XL
C                                       INPUT MASS FLOW,MDOTIN (KG/SEC)
C                                       MASS FRACTION (WET, ASH) CO2,H2O,N2,O2
C                                       RELATIVE MASS FLOWS,MDOTxx (INPUT=1 BASIS)
C                                       ZONE GAS TEMPERATURES,TEMP
C                                       AXIAL AND RADIAL INJECTION INDICES, II,JI
C                                       NUMBER OF RANDOM RUNS TO OBTAIN STATISTICALLY
C                                          AVERAGED OUTPUT
C
      READ(1,7)NINCIN
      DO 999 INCINO = 1,NINCIN
      READ(1,5)CASE
 5    FORMAT(80A1)
      READ(1,7)IX,IY
 7    FORMAT(2I4)
      READ(1,10)(R(J),J=1,IY)
 10   FORMAT(10F8.5)
      READ(1,12)(XL(J),J=1,IX)
 12   FORMAT(10F8.5)
      READ(1,15)FCO2,FH2O,FN2,FO2
 15   FORMAT(4F8.5)
      SUMASS=(FCO2/.044)+(FH2O/.018)+(FN2/.028)+(FO2/.032)
      IXPLUS=IX+1
      DO 30 I=1,IXPLUS

      IF(IOUT(3).EQ.1) CALL DRPPRT
C
      RETURN
      END
```

# APPENDIX E

# SWIRLING, TURBULENT FLAME TESTS

# APPENDIX E1

# CONDENSED DATA SHEETS

## BASELINE TEST CONDITIONS

Fuel: Natural Gas
Oxidizer: Air
Load: 310 kBtu/hr (91 kW)
Excess Air: 30% (equivalence ratio, $\phi$ = 0.77)

### Input Parameters

| | Fuel Injection Parameters | | | Air Injection Parameters | | |
|---|---|---|---|---|---|---|
| Flame Type | Preheat (°F) | Angle | Velocity (Fps) | Preheat (°F) | Swirl * | Throat Velocity |
| A/B | 60 | 0° (axial) | 149 | 75° | 0.65 | 91 |
| B | 60 | 0° (axial) | 149 | 75° | 1.3 | 91 |
| C | 60 | 45° | 142 | 75° | 1.3 | 91 |

### Output Data

| | | Stack Emissions (dry) | | | | |
|---|---|---|---|---|---|---|
| Flame Type | Flame Length (in) | $O_2$ (%) | $CO_2$ (%) | NO (ppm)* | CO (ppm) | UHC (ppm) |
| A/B | 20 - 24 | | | | | |
| B | 6 - 7 | 6.2 | 9.0 | 30 - 50 | ~5 | <1 |
| C | 4 - 5 | | | | | |

*at zero percent $O_2$

## BASELINE TEST RESULTS

12/15, 16, 17/85 ·
Flame Type: C

| Test Pt. | Axial Location (in) | Radial Location (in) | Temp. (°F) | V (Fps) | $V_x$ (Fps) | $V_y$ (Fps) | $V_z$ (Fps) |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 8 | 1531 | 30 | -15 | -25 | -5 |
| 2 | | 6 | 1573 | 30 | -15 | -25 | -5 |
| 3 | | 5 | 1566 | 18 | -12 | -10 | -5 |
| 4 | | 4 | 1571 | 18 | -10 | -10 | -10 |
| 5 | | 3 | 1598 | 20 | -3 | -10 | -17 |
| 6 | | 2 | 1621 | 95 | 85 | | -35 |
| 7 | | 1 | 2633 | 50 | -10 | | -45 |
| 8 | | 0 | 2518 | 40 | -30 | 15 | -20 |
| 9 | 10 | 8 | 1644 | 17 | -13 | -10 | -5 |
| 10 | | 6 | 1651 | 18 | -13 | -5 | -10 |
| 11 | | 5 | 1664 | 18 | -10 | -5 | -15 |
| 12 | | 4 | 1690 | 17 | -5 | 0 | -15 |
| 13 | | 3 | 1757 | 23 | 15 | 8 | -15 |
| 14 | | 2 | 1841 | 38 | 32 | 10 | -17 |
| 15 | | 1 | 1924 | 45 | 40 | 15 | -20 |
| 16 | | 0 | 2035 | 43 | 35 | 15 | -20 |
| 17 | 18 | 8 | 1688 | 17 | -13 | -5 | |
| 18 | | 6 | 1702 | 18 | | | -15 |
| 19 | | 4 | 1717 | 17 | 10 | -6 | -13 |
| 20 | | 2 | 1758 | 19 | 14 | | -12 |
| 21 | | 0 | 1798 | 22 | 18 | | -10 |
| 22 | 26 | 8 | 1678 | 17 | | -8 | -10 |
| 23 | | 4 | 1727 | 17 | | -5 | -15 |
| 24 | | 0 | 1771 | 16 | | | -10 |
| 25 | [illegible] | 8 | 1653 | — | — | — | — |
| 26 | | 4 | 1661 | — | — | — | — |
| 27 | | 0 | 1693 | — | — | — | — |

## FLOW TEST MATRIX

| Test Pt. | Liquid | Orifice (in) | Jet Velocity (Fps) | Freq. Div. | Inj. Angle/ Radius (°/in) | Flame Type | Date | Comments |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | .004 | 35 | 64 | 30/5.5 | C | 12/4 | Nominal |
| 2 | 1 | .004 | 35 | 1 | 30/5.5 | C | 12/6 | Spacing |
| 3 | " | " | " | 2 | " | " | 12/6 | " |
| 4 | " | " | " | 4 | " | " | 12/5 | " |
| 5 | " | " | " | 8 | " | " | 12/5 | " |
| 6 | " | " | " | 16 | " | " | 12/6 | " |
| 7 | 1 | .004 | 24 | 64 | 30/5.5 | C | 12/11 | Velocity |
| 8 | " | " | 46 | " | " | " | 12/11 | " |
| 9 | 1 | .006 | 35 | 64 | 30/5.5 | C | 12/12 | Size |
| 10 | " | .008 | " | " | " | " | 12/12 | " |
| 11 | 1 | .004 | 35 | 1 | 0/7 | C | 12/3 | Inj. Angle |
| 12 | " | " | " | 64 | 0/7 | " | 12/3 | " |
| 13 | " | " | " | " | 45/4.9 | " | 12/13 | " |
| 14 | 1 | .004 | 35 | 64 | 30/5.5 | A/B | 12/19 | Flame Type |

## HOT FLOW TEST RESULTS

| Test | Ignition Point | | | Burnout Point | | | Stack Emissions | | | CO (ppm, dry) Axial/Radial Loc | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pt | x(in) | r(in) | θ(°) | x(in) | r(in) | θ(°) | $O_2$(%) | $CO_2$(%) | CO | 18"/0" | 18"/4" | 18"/8" | 18"/3" |
| C* | -- | -- | -- | -- | -- | -- | 6.2 | 9.0 | ~5 | 75 | 45 | 5- 7 | 15 |
| A/B* | -- | -- | -- | -- | -- | -- | 6.2 | 9.0 | ~5 | 575 | 335 | -- | -- |
| 1 | 4- 6 | 2-3 | 20- 30 | 17-20 | 2- 8 | 110-120 | 6.6 | 8.9/8.8 | ~5 | 20 | 35 | 10 | 10 |
| 2 | 5 | 2-3 | 10- 20 | 9.5-11 | 0- 1 | 90 | 6.2/5.55 | 9.0/9.5 | ~5 | 25 | 500-625 | 125-150 | 15 |
| | 12-14 | 2-4 | 110-140 | 26-32 | 9-10 | 160 | | | | | | | |
| 3 | 4- 5 | 3 | 20- 30 | 10 | 1.5- 2 | 70- 80 | 6.3/6.0 | 9.0/9.2 | ~5 | 20 | 140-220 | 70 | 20-25 |
| | 12-14 | 2 | 120 | 26-27 | 9 | 160-170 | | | | | | | |
| 4 | 4.5- 5 | 2.5-3 | 30 | 20-25 | 6- 9 | 110 | 6.15/6.1 | 9.0/9.1 | ~5 | 25 | 80 | 30 | 20 |
| 5 | 4- 5 | 2-3 | 30 | 17-19 | 4- 8 | 120 | 6.1/6.0 | 9.1/9.2 | ~5 | 20 | 65 | 15 | 15 |
| 6 | 4- 5 | 2 | 10- 20 | 16-17 | 4- 5 | 100-110 | 6.05/6.0 | 9.1 | ~5 | 20-25 | 40- 55 | 10 | 10 |
| | 10-12 | 3-3.5 | 90 | | | | | | | | | | |
| 7 | | | | <6 | (entrained) | | 6.2 | 9.0 | ~5 | 90 | 60 | 6 | 25 |
| 8 | 4- 5 | 2-2.5 | 30 | 9-10 | 3 | 45- 60 | 6.25 | 9.0 | ~5 | 95 | 95 | 10 | 25 |
| | 11-13 | 3-4 | 60 | 24-27 | 5- 8 | 110-135 | | | | | | | |
| 9 | 4- 5 | 2.5-3 | 20- 30 | 9-11 | 1 | 60 | 6.05 | 9.0 | ~5 | 95 | 75 | 7-10 | 45 |
| | 14-18 | 0-6 | 90-110 | 22-28 | 10 | 135 | | | | | | | |
| 10 | 5 | 3 | 20- 30 | 9-11 | 0-1.5 | 60 | 6.1/6.05 | 9.1 | ~5 | 50 | 47 | 7-10 | 15 |
| | 16-18 | 4-5 | 90-100 | 26-30 | 6-10 | 120-135 | | | | | | | |
| 11 | 7- 9 | 6-7 | 30 | 28-32 | 6- 7 | 30 | 6.05/5.7 | 9.1/9.5 | ~5 | -- | -- | -- | 10 |
| 12 | 7-10 | 6-7 | 30 | 18-20 | 6- 7 | 30 | 6.1/6.05 | 9.1/9.1 | ~5 | -- | -- | -- | 15 |
| 13 | 1- 3 | 2 | 20- 30 | 7.5- 8 | 2- 3 | 60 | 6.3 | 8.9 | ~5 | 75 | 50 | 7-10 | 25 |
| | 7-11 | 2-3 | 90 | 18-20 | 4- 5 | 90 | | | | | | | |
| 14 | 4- 5 | 2-3 | 10 | 14-15 | 1- 3 | 100-120 | 6.2 | 9.0 | ~5 | 750 | 320 | -- | |

*Type Baseline

# APPENDIX E2

## COMPUTER PROGRAM

COMPUTER PROGRAM

```
           (filename = DROP2D2.FOR)
        SUBROUTINE DPMVV
C
C       Written by Mark Sheldon for EER, 4/85
C       Revised by Susan Robinson for EER 9/86
C
C       PURPOSE:
C           DRPMOV (DRoPlet MOVe) calculates the motion, heating, and
C           evaporation of a single droplet during a single timestep.
C
C           LOCAL VARIABLES
C
        REAL NUSELT,N
        LOGICAL PRTLIN,WZCOLD
C
C           COMMON VARIABLES FROM SUBROUTINE DROP
C
        INTEGER COUNT1, COUNT2,RMAXP,XMAXP
        LOGICAL BOIL, CNVRG, GETOUT
C
        REAL MDOTXP, MDOTXN, MDOTYP, MDOTYN
        INTEGER RMAX,XMAX
        LOGICAL*1 CASE(80)
        PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
C           COMMON VARIABLES FROM SUBROUTINE SETINJ
C
        REAL LHELIQ, LHELIQ1, LHELIQ2
        REAL NSTEP
        INTEGER START1, START2
        INTEGER IA(55)
        LOGICAL*1 INCASE
C
C           COMMON VARIABLES FROM SUBROUTINE YV
C
        REAL LDINIT
C
        COMMON/MOVECB/
     1          DTIME , DTSAV , OLDDT , TIME
     2         ,DIAM  , UGAS  , VGAS  , PRANDT
     3         ,IINEW , JINEW , COUNT1, COUNT2
     4         ,BOIL  , CNVRG,  GETOUT, DT, START1, START2
C
        COMMON/INPUT/
     1          MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1         ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     2         ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
        COMMON/ZDIMCB/
     1          IX, IY, IXPLUS, IYPLUS
C
        COMMON/ZBDYCB/
     1          UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
     2         ,XBDY(XMAXP)  , YBDY(RMAXP)
     3         ,TWALL(XMAX,RMAX)
C
```

```
      COMMON/GASCB/
     1         CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2        ,FO2, FN2, FCO2, FH2O
C
      COMMON/LIQCB/
     1         TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/DROPCB/
     1         XPOLD, YPOLD, UPOLD, VPOLD, VINIT, SPACE, C, XPINIT
     2         , RNDNUM, SDINIT, JRAND, LDINIT, DPOLD, TPOLD
     3        , DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/PARMCB/
     1         NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2        ,MAXSTP, NRAMP, NDROP, TRNO
C
          COMMON/PRTCB/
     1         CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
C         DENSITY (KG M**-3), IDEAL GAS AT 1 ATM
C            (SUMASS IS GMOLES PER KG OF GAS MIXTURE)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
C           TRANSFER NUMBER (FOR EQUATION OF dD/dt AND ETAE)
C
      IF(IDUM.EQ.2) GO TO 200
      TRANSNO = (CPGAS(II,JI) * (TEMP(II,JI)-TLIQ) + HCOMLQ * FO2 /
     1          AFMRAT) / LHELIQ
      GO TO 210
200   CONTINUE
      IF(IOUT(7).EQ.0) TRANSNO = FO2 / AFMRAT
      IF(IOUT(7).EQ.1) TRANSNO = TRNO
210   CONTINUE
C
C         OUTPUT LOGIC
C
      PRTLIN = .FALSE.
      IF(COUNT2.LE.NPRT1) PRTLIN = .TRUE.
      IF(MOD(COUNT2,NPRT2).EQ.0) PRTLIN = .TRUE.
      WZCOLD = .FALSE.
      STEPM = 0.100
      DUM1 = 1.0 - (DIAM/DINIT)**3.
      MGOAL1 = INT(DUM1/STEPM)
C
C         ADJUST TIMESTEP FOR EARLY PART OF ZONE
C
```

```
      DTIME = DTSAV
      IF(COUNT2.LE.NRAMP.AND.COUNT1.EQ.1)
     1        DTIME = DTSAV*FLOAT(COUNT2)/FLOAT(NRAMP)
C
C         ADJUST TIMESTEP FOR EVAPORATING DROPLET
C
        DUM1 = DIAM/DINIT
        IF(DUM1.LT.0.3) DUM1 = 0.3
        DTIME = DTIME * DUM1*DUM1
C
C         UPDATE DROP POSITION
C
      XPNEW = XPOLD + UPOLD*DTIME
      DUM1 = XBDY(II+1) + 1.0E-8
      IF(XPNEW.LT.DUM1) GOTO 300
          IINEW = II + 1
          DTIME = (XBDY(II+1) - XPOLD) /UPOLD
          XPNEW = XBDY(II+1)
300   CONTINUE
      DUM2 = XBDY(II) - 1.0E-8
      IF(XPNEW.GT.DUM2) GOTO 310
          IINEW = II - 1
          DTIME = (XBDY(II) - XPOLD) /UPOLD
          XPNEW = XBDY(II)
310   CONTINUE
C
      YPNEW = YPOLD + VPOLD*DTIME
      DUM3 = YBDY(JI+1) + 1.0E-8
      IF(YPNEW.LT.DUM3) GOTO 320
          JINEW = JI + 1
          DTIME = (YBDY(JI+1) - YPOLD) /VPOLD
          YPNEW = YBDY(JI+1)
320   CONTINUE
      DUM4 = YBDY(JI) - 1.0E-8
      IF(YPNEW.GT.DUM4) GOTO 330
          JINEW = JI - 1
          DTIME = (YBDY(JI) - YPOLD) /VPOLD
          YPNEW = YBDY(JI)
330   CONTINUE
C
C         CHECK FOR NEGATIVE OR HUGE TIMESTEPS NEAR BOUNDARY
C          (NEGATIVE TIMESTEP MEANS XPOLD WAS ACTUALLY IN NEW ZONE)
C          (HUGE TIMESTEP MEANS DROPLET VELOCITY VERY SMALL)
C
      IF(II.EQ.IINEW.AND.JI.EQ.JINEW) GO TO 340
          DUM1 = DTIME
          IF(DUM1.GE.0.0) GOTO 341
            DTIME = OLDDT
            GETOUT = .TRUE.
            RETURN
341       CONTINUE
          IF(DUM1.GE.1.E22) DTIME = OLDDT
340   CONTINUE
C
C         UPDATE DROPLET VELOCITY AT NEW POSITION
```

```
C         (CDRE IS DRAG COEFF X REYNOLD NUMBER)
C
      VRELX   = UPOLD - UGAS
      VRELY   = VPOLD - VGAS
      VRELMAG = SQRT( VRELX**2 + VRELY**2 )
      VDMAG   = SQRT( UPOLD**2 + VPOLD**2 )
C
C         ALLOWANCE FOR GRAVITY IN THE +X OR +Y DIRECTION
C
      GRAVX = 0.0
      GRAVY = 0.0
      IF(IOUT(5).EQ.1) GRAVX = 9.81
      IF(IOUT(6).EQ.1) GRAVY = 9.81
      IF(IOUT(4).EQ.1) GRAVX = 0.0
      IF(IOUT(4).EQ.1) GRAVY = 0.0
      IF(IOUT(4).EQ.3) GRAVX = 0.0
      IF(IOUT(4).EQ.3) GRAVY = 0.0
C
      RENOLD = DIAM * DENS(SUMASS,TEMP(II,JI)) * VRELMAG / DVISCG(II,JI)
C
      IF(RENOLD.LE.80) CDINF = 27. * RENOLD**(-0.84)
      IF(RENOLD.GT.80.AND.RENOLD.LT.1.E4)
     1          CDINF = 0.271 * RENOLD**(0.217)
      IF(RENOLD.GE.1.E4) CDINF = 2.
C
C         ADJUST DRAG COEFFICIENT FOR CLOSELY SPACED DROPLETS
C
      SPACE = VDMAG * SDINIT / VINIT
      IF (SPACE.LT.DIAM) SPACE = DIAM
      D1 = ALOG(SPACE/DIAM)
      CD2 = 0.755/RENOLD + 34.8 * RENOLD**(-1.009) * (SPACE/DIAM-1.)
      EXP1 = -1./0.7072
      CD = (CDINF ** (-0.7072) + CD2 **(-0.7072)) **EXP1
C
      IF(IOUT(4).EQ.4) CD = CDINF
C
C         ETAE ACCOUNTS FOR EFFECT OF MASS TRANSFER (EVAP) ON DRAG
C
      ETAE = 1.
      IF(BOIL) ETAE  = 1. / ( 1. + TRANSNO )
      IF(IOUT(4).EQ.7) ETAE = 1.0
      CDINF = CDINF * ETAE
      CD    = CD * ETAE
C
C
      VR1MAG = VRELX * UPOLD/VDMAG + VRELY * VPOLD/VDMAG
      VR1X = VR1MAG * UPOLD/VDMAG
      VR1Y = VR1MAG * VPOLD/VDMAG
C
      VR2X = VRELX - VR1X
      VR2Y = VRELY - VR1Y
      VR2MAG = SQRT (VR2X**2 + VR2Y**2)
C
      FD1 = CD * DENS(SUMASS,TEMP(II,JI)) * 3.14159 * DIAM**2.
     1        * VR1MAG**2./8.
```

```
      FD2 = CDINF * DENS(SUMASS,TEMP(II,JI)) * 3.14159 * DIAM**2.
     1        * VR2MAG**2./8.
C
      IF(IOUT(4).EQ.2) FD1 = 0.0
      IF(IOUT(4).EQ.2) FD2 = 0.0
      IF(IOUT(4).EQ.3) FD1 = 0.0
      IF(IOUT(4).EQ.3) FD2 = 0.0
C
      FD1X = -FD1 * UPOLD/VDMAG
      FD1Y = -FD1 * VPOLD/VDMAG
      FD2X = -FD2 * VR2X/VR2MAG
      FD2Y = -FD2 * VR2Y/VR2MAG
C
      DMASS =  RHOLIQ * DIAM**3. * 3.14159 / 6.
C
      UPNEW = UPOLD + (FD1X + FD2X) / DMASS * DTIME + GRAVX * DTIME
      VPNEW = VPOLD + (FD1Y + FD2Y) / DMASS * DTIME + GRAVY * DTIME
C
C         UPDATE GAS VELOCITY AT NEW POSITION
C
      UGAS = UBDY(II,JI) + (UBDY(II+1,JI) - UBDY(II,JI))
     1                        *(XPNEW - XBDY(II)) / (XBDY(II+1) - XBDY(II))
C
      VGAS = VBDY(II,JI) + (VBDY(II,JI+1) - VBDY(II,JI))
     1                        *(YPNEW - YBDY(JI)) / (YBDY(JI+1) - YBDY(JI))
C
C         ETAS ACCOUNTS FOR EFFECT OF DROPLET SPACING ON EVAPORATION
C
      DUMO = DINIT / SPACE
      ETAS = 1 - DUMO + DUMO**2 - DUMO**3 + DUMO**4 - DUMO**5 + DUMO**6
      IF(DUMO.GT.0.5) ETAS = 0.62
      IF(DUMO.GT.0.7) ETAS = 0.55
      IF(DUMO.GT.0.9) ETAS = 0.50
      IF(DIAM.LT.DINIT3) ETAS = 1.0
      IF(IOUT(4).EQ.6) ETAS = 1.0
C
C         CASE WHERE DROP IS BOILING
C
      IF(.NOT.BOIL) GOTO 400
C
      CBOIL = 8. * TCONDG(II,JI) / RHOLIQ / CPGAS(II,JI)
     1        * ALOG(1. + TRANSNO)
          DUM2 = DIAM*DIAM - CBOIL*(1. + 0.23*RENOLD**0.5)*DTIME*ETAS
          DUM3 = DUM2/DINIT/DINIT
          IF(DUM3.GT.1.E-12) GOTO 401
            DIAM = 0.
            GETOUT = .TRUE.
            XPOLD = XPNEW
            YPOLD = YPNEW
            UPOLD = UPNEW
            VPOLD = VPNEW
            TIME   = TIME + DTIME
            IF(IOUT(3).EQ.1) WRITE(2,402)
            IF(IOUT(3).EQ.1) WRITE(7,402)
402         FORMAT(1X,'DROPLET CONSIDERED EVAPORATED WHEN DIAMETER IS'
     1                 ,' 1.E-6 OF INITIAL VALUE')
            RETURN
401       CONTINUE
          DIAM = DUM2**0.5
          TLNEW = TLIQ
C
C         CASE WHERE DROP TEMPERATURE IS CHANGING
C
400    CONTINUE
       IF(BOIL) GOTO 450
          NUSELT = 2. + 0.6 * (RENOLD**0.5) * (PRANDT**(1./3.))
          DUM3   = 6. *NUSELT *TCONDG(II,JI) /RHOLIQ /DIAM /DIAM /CPLIQ
          TLNEW  = TEMP(II,JI) - (TEMP(II,JI)-TLIQ) * EXP(-DUM3 * DTIME)
C
C         CASE WHERE DROP STARTS BOILING DURING STEP (STARTS TO SHRINK TOO)
C
       IF(TLNEW.LT.TBOIL) GOTO 450
          DUM4 = DTIME
     1          -(1./DUM3)*ALOG((TEMP(II,JI)-TLIQ)/(TEMP(II,JI)-TBOIL))
          CBOIL = 8. * TCONDG(II,JI) / RHOLIQ / CPGAS(II,JI)
     1         *ALOG(1. + TRANSNO )
          DUM2 = DIAM*DIAM - CBOIL*(1. + 0.23*RENOLD**0.5)*DUM4*ETAS
          DUM3 = DUM2/DINIT/DINIT
          IF(DUM3.GT.1.E-12) GOTO 451
            DIAM = 0.
            GETOUT = .TRUE.
            XPOLD = XPNEW
            YPOLD = YPNEW
            UPOLD = UPNEW
            VPOLD = VPNEW
            TIME   = TIME + DTIME
            WRITE(2,402)
            RETURN
451       CONTINUE
          DIAM = DUM2**0.5
          TLNEW = TBOIL
          BOIL = .TRUE.
          WZCOLD = .TRUE.
         WRITE(2,600) TIME,XPNEW,YPNEW,DIAM,TLNEW
         WRITE(7,600) TIME,XPNEW,YPNEW,DIAM,TLNEW
600      FORMAT(/ ' DROP STARTS TO BOIL AT TIME = ',E10.3,' SEC:'/
     1        ' X (M) = ',F7.4,' Y (M) = ',F7.4,' D (M) = ',
     2          E10.3,' T (K) = ',F7.1/)
C
C         TEST FOR VELOCITY CONVERGENCE
C
450    CONTINUE
       IF(DIAM.GE.DINIT2) GO TO 452
         IF(IDUM.EQ.0) WRITE(2,440) TIME,XPNEW,YPNEW,DIAM,TLNEW
         IF(IDUM.EQ.0) WRITE(7,440) TIME,XPNEW,YPNEW,DIAM,TLNEW
440      FORMAT(/ ' DROP ENTERS PHASE 2 AT TIME = ',E10.3,' SEC:'/
     1        ' X (M) = ',F7.4,' Y (M) = ',F7.4,' D (M) = ',
     2          E10.3,' T (K) = ',F7.1/)
       IF(IDUM.EQ.0) IDUM = 1
       TBOIL = TBL2
```

```
        CPLIQ = CPLIQ2
        LHELIQ = LHELIQ2
        RHOLIQ = RHOLIQ2
        HCOMLQ = HCOMLQ2
        AFMRAT = AFMRAT2
        IF(DIAM.GE.DINIT3) GO TO 452
          IF(IDUM.EQ.1) WRITE(2,445) TIME,XPNEW,YPNEW,DIAM,TLNEW
          IF(IDUM.EQ.1) WRITE(7,445) TIME,XPNEW,YPNEW,DIAM,TLNEW
445       FORMAT(/ ' DROP ENTERS PHASE 3 AT TIME = ',E10.3,' SEC:'/
     1           ' X(M) = ',F7.4,' Y (M) = ',F7.4,' D (M) = ',
     2           E10.3,' T (K) = ',F7.1/)
          IDUM = 2
          TBOIL = TBL3
          CPLIQ = CPLIQ3
          RHOLIQ = RHOLIQ3
          AFMRAT = AFMRAT3
          IF(DIAM.GE.DINIT4) GO TO 452
          GETOUT = .TRUE.
          XPOLD = XPNEW
          YPOLD = YPNEW
          UPOLD = UPNEW
          VPOLD = VPNEW
          TIME = TIME + DTIME
          WRITE(2,405)DINIT4,DIAM
          WRITE(7,405)DINIT4,DIAM
405       FORMAT(' DROPLET CONSIDERED GONE WHEN DIAMETER IS'
     1           ,' LESS THAN ',E10.3,' M'/ ' D (M) = ',E10.3)
          DIAM = 0.0
          RETURN
452   CONTINUE
      IF(TLNEW.LT.TBOIL) BOIL = .FALSE.
      DUM1 = ABS(UGAS-UPNEW)
      DUM2 = ABS(VGAS-VPNEW)
      IF(DUM1.GT.TOL1.OR.DUM2.GT.TOL1) GOTO 460
        IF(.NOT.CNVRG) WRITE(2,455) TOL1
455     FORMAT(1X,'DROPLET AT STREAM VELOCITY TO WITHIN ',E10.3,' M/S')
        CNVRG = .TRUE.
460   CONTINUE
C
C         NEW QUANTITIES BECOME OLD FOR NEXT TIMESTEP
C
      XPOLD = XPNEW
      YPOLD = YPNEW
      UPOLD = UPNEW
      VPOLD = VPNEW
      TLIQ  = TLNEW
      TIME  = TIME + DTIME
C
C         DEBUG OUTPUT FOR TIMESTEP
C
      DUM1 = DIAM * 1.E6
      DPOLD = DUM1
      TPOLD = TLIQ
      DUM2 = 1. - (DIAM/DINIT)**3.
      DUM3 = CDRE / RENOLD
      MGOAL2 = INT(DUM2/STEPM)
      IF(MGOAL1.NE.MGOAL2) PRTLIN=.TRUE.
      IF(WZCOLD)  PRTLIN = .TRUE.
      IF(PRTLIN.AND.IOUT(3).EQ.1) WRITE(2,510)II,JI,COUNT2,TIME,XPOLD
     1                 ,YPOLD,UPOLD,VPOLD,TLIQ,DUM1,DUM2,renold
510   FORMAT(' ',I3,I3,I5,E10.3,2(F7.4),2(F7.3),F7.1,F8.2,F8.3,f7.3)
C
      RETURN
      END
C ------------------------------------------------------------------
      SUBROUTINE SETPRT
C
C     Written by Mark Sheldon for EER, 4/18/85
C
C     PURPOSE:
C         SETPRT (SETup PRinTout) prints variables from main program
C         and from subroutine SETINJ.
C
C         COMMON VARIABLES FROM MAIN PROGRAM
C
      LOGICAL*1 CASE(80)
C
C         COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      REAL LHELIQ, LHELIQ1, LHELIQ2
      REAL NSTEP
      INTEGER RMAX,XMAX
      INTEGER RMAXP,XMAXP
      LOGICAL*1 INCASE
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
      COMMON/ZDIMCB/
     1        IX, IY, IXPLUS, IYPLUS
C
      COMMON/ZBDYCB/
     1          UBDY(XMAXP,RMAX), VBDY(XMAX,RMAXP)
     2         ,XBDY(XMAXP)  , YBDY(RMAXP)
     3         ,TWALL(XMAX,RMAX)
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1          NSTEP, DSAFE, TSAFE, ESAFE, TOL1
     2         ,MAXSTP, NRAMP, NDROP, TRNO
C
      COMMON/PRTCB/
     1          CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
C        DEBUG OUTPUT HEADER
C
      WRITE(2,200)
200   FORMAT(' ',' ','*** DROPLET INJECTION MODEL ***',/)
C
      WRITE(2,220)(CASE(I),I=1,70)
220   FORMAT(1X,70A1)
C
      WRITE(2,240)(INCASE(I),I=1,70)
240   FORMAT(1X,70A1,/)
C
      WRITE(2,241)
241   FORMAT(1X,'NOMENCLATURE:')
C
      WRITE(2,242)
242   FORMAT(4X,'X        = AXIAL  DISTANCE (M)')
C
      WRITE(2,243)
243   FORMAT(4X,'Y        = RADIAL DISTANCE (M)')
C
      WRITE(2,244)
244   FORMAT(4X,'U        = AXIAL  VELOCITY (M/S)')
C
      WRITE(2,245)
245   FORMAT(4X,'V        = RADIAL VELOCITY (M/S)')
C
      WRITE(2,246)
246   FORMAT(4X,'I        = AXIAL  ZONE INDEX')
C
      WRITE(2,247)
247   FORMAT(4X,'J        = RADIAL ZONE INDEX')
C
      WRITE(2,248)
248   FORMAT(4X,'XBDY(I)  = LOCATION OF  LEFT-HAND   BOUNDARY'
     1           ,' OF ZONE I,J')
C
      WRITE(2,249)
249   FORMAT(4X,'YBDY(I)  = LOCATION OF INNER RADIAL BOUNDARY'
     1           ,' OF ZONE I,J')
C
      WRITE(2,250)
250   FORMAT(4X,'UBDY(I,J)= AXIAL  GAS VELOCITY AT BDY'
     1           ,' BETWEEN I,J AND I-1,J')
C
      WRITE(2,251)
251   FORMAT(4X,'VBDY(I,J)= RADIAL GAS VELOCITY AT BDY'
     1           ,' BETWEEN I,J AND I,J-1')
C
      WRITE(2,260)IX,IY
260   FORMAT(1X,/,1X,'SOLUTION GRID: '
     1           ,I3,' AXIAL BY ',I3,' RADIAL ZONES',/)
C
      I1 = IXPLUS
      IF(IYPLUS.GT.IXPLUS) I1=IYPLUS
      DO 300 I = 1,I1
         IF(I.LE.IXPLUS.AND.I.LE.IYPLUS)WRITE(2,320)I,XBDY(I),I,YBDY(I)
320      FORMAT(4X,'XBDY(',I3,') : ',F8.4,5X,'YBDY(',I3,') : ',F8.4)
         IF(I.GT.IXPLUS)WRITE(2,340)I,YBDY(I)
340      FORMAT(4X,25X,'YBDY(',I3,') : ',F8.4)
         IF(I.GT.IYPLUS)WRITE(2,360)I,XBDY(I)
360      FORMAT(4X,'XBDY(',I3,') : ',F8.4)
300   CONTINUE
C
      WRITE(2,400)(J,J=1,IY)
400   FORMAT(1X,/,1X,'AXIAL GAS VELOCITY AT ZONE BOUNDARIES (M/S):'
     1          ,/,3X,'I:',1X,10(2X,:,'J=',I2,2X))
      DO 420 I = 1, IXPLUS
         WRITE(2,440) I,(UBDY(I,J),J=1,IY)
440      FORMAT(1X,I3,11(1X,F7.2))
420   CONTINUE
C
      WRITE(2,460)(J,J=1,IYPLUS)
460   FORMAT(1X,/,1X,'RADIAL GAS VELOCITY AT ZONE BOUNDARIES (M/S):'
     1          ,/,3X,'I:',1X,10(2X,:,'J=',I2,2X))
      DO 480 I = 1, IX
         WRITE(2,500) I,(VBDY(I,J),J=1,IYPLUS)
500      FORMAT(1X,I3,11(1X,F7.2))
480   CONTINUE
C
      WRITE(2,520)
520   FORMAT(1X,/,1X,'INITIAL DROPLET PROPERTIES:')
C
      WRITE(2,540)TINIT
540   FORMAT(4X,'INITIAL DROP TEMP     (K) = ',F7.1)
C
      WRITE(2,560)TBL1
560   FORMAT(4X,'LIQUID BOILING TEMP 1 (K) = ',F7.1)
C
      WRITE(2,580)RHOLIQ1
580   FORMAT(4X,'LIQUID DENSITY 1 (KG M**-3) = ',E10.3)
C
      WRITE(2,600)CPLIQ1
600   FORMAT(4X,'LIQUID HEAT CAPACITY 1 (M**2 S**-2 K**-1) = ',E10.3)
C
      WRITE(2,620)LHELIQ1
620   FORMAT(4X,'LATENT HEAT OF EVAP. 1 (M**2 S**-2)  = ',E10.3)
C
      WRITE(2,630)AFMRAT1
630   FORMAT(4X,'AIR/FUEL MASS RATIO 1 = ',F10.4/)
C
      WRITE(2,640)
640   FORMAT(1X,'PROGRAM PARAMETERS:')
C
      WRITE(2,660) NDROP
660   FORMAT(4X,'NUMBER OF DROPLETS INJECTED  =',I8)
C
      WRITE(2,680)MAXSTP
680   FORMAT(4X,'MAXIMUM NUMBER OF STEPS IN LOOP, MAXSTP = ',I10)
```

```
C
      WRITE(2,700) NRAMP
700   FORMAT(4X,'TIMESTEP SIZE INCREASED OVER ',I4
     1         ,' STEPS, 1ST ZONE')
C
      WRITE(2,720)NSTEP
720   FORMAT(4X,'APPROX. MIN. NO. STEPS IN ZONE,  NSTEP = ',F7.3)
C
      WRITE(2,740)DSAFE
740   FORMAT(4X,'SAFETY FACTOR FOR DRAG TIMESTEP, DSAFE = ',F7.3)
C
      WRITE(2,760)TSAFE
760   FORMAT(4X,'SAFETY FACTOR FOR TEMP TIMESTEP, TSAFE = ',F7.3)
C
      WRITE(2,780)ESAFE
780   FORMAT(4X,'SAFETY FACTOR FOR EVAP TIMESTEP, ESAFE = ',F7.3)
C
      RETURN
      END
C -----------------------------------------------------------------
      SUBROUTINE GASPRTV
C
C     Written by Mark Sheldon for EER, 4/17/85
C
C     PURPOSE:
C        GASPRT (GAS PRinT) prints the important input and output
C        for subroutine GPROP.
C
C        COMMON VARIABLES FROM MAIN PROGRAM
C
      REAL MDOTXP, MDOTXN, MDOTYP, MDOTYN
      LOGICAL*1 CASE(80)
C
C        COMMON VARIABLES FROM SUBROUTINE SETINJ
C
      INTEGER RMAX,XMAX ,RMAXP,XMAXP
      LOGICAL*1 INCASE
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
      COMMON/INPUT/
     1         MDOTXP(XMAXP,RMAX),MDOTXN(XMAXP,RMAX)
     1        ,MDOTYP(XMAX,RMAXP),MDOTYN(XMAX,RMAXP),SUMASS
     2        ,R(RMAX), TEMP(XMAX,RMAX), XL(XMAX), II, JI
C
      COMMON/ZDIMCB/
     1         IX, IY, IXPLUS, IYPLUS
C
      COMMON/GASCB/
     1         CPGAS(XMAX,RMAX), DVISCG(XMAX,RMAX), TCONDG(XMAX,RMAX)
     2        ,FO2, FN2, FCO2, FH2O
C
      COMMON/PRTCB/
     1         CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
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```
C          OUTPUT FILE
C
C          OUTPUT HEADER
C
      WRITE(2,99)(CASE(I),I=1,70)
99    FORMAT(1X,/,1X,80A1)
C
      WRITE(2,200)(INCASE(I),I=1,70)
200   FORMAT(1X,70A1)
C
      WRITE(2,220)FO2,FN2,FCO2,FH2O
220   FORMAT(1X,/,1X,'MASS FRACTIONS:',/,1X
     1         ,'O2=',F6.4,3X,'N2=',F6.4,3X,'CO2=',F6.4,3X,'H2O=',F6.4)
C
C          INPUT ARRAYS
      WRITE(2,300)(J,J=1,IY)
300   FORMAT(1X,/,1X,'ZONE TEMPERATURE:',/,1X,'I:',1X
     1                  ,10(2X,:,'J=',I2,1X))
C
      DO 350 I = 1, IX
          WRITE(2,360) I,(TEMP(I,J),J=1,IY)
360       FORMAT(1X,I3,10(1X,F6.1))
350   CONTINUE
C
C          OUTPUT ARRAYS
C
      WRITE(2,400)(J,J=1,IY)
400   FORMAT(1X,/,1X,'ZONE HEAT CAPACITY (M*M/S/S/K):'
     1              ,/,1X,'I:',1X,10(1X,:,2X,'J=',I2,2X))
C
      DO 410 I = 1, IX
          WRITE(2,420) I,(CPGAS(I,J),J=1,IY)
420       FORMAT(1X,I3,10(1X,F8.1))
410   CONTINUE
C
      WRITE(2,500)(J,J=1,IY)
500   FORMAT(1X,/,1X,'ZONE DYNAMIC VISCOSITY (KG/M/S):'
     1              ,/,1X,'I:',1X,10(4X,:,'J=',I2,4X))
C
      DO 510 I = 1, IX
          WRITE(2,520) I,(DVISCG(I,J),J=1,IY)
520       FORMAT(1X,I3,10(1X,E11.4))
510   CONTINUE
C
      WRITE(2,600)(J,J=1,IY)
600   FORMAT(1X,/,1X,'ZONE THERMAL CONDUCTIVITY (KG/S/S/S/K):'
     1              ,/,1X,'I:',1X,10(4X,:,'J=',I2,4X))
C
      DO 610 I = 1, IX
          WRITE(2,620) I,(TCONDG(I,J),J=1,IY)
620       FORMAT(1X,I3,10(1X,F11.6))
610   CONTINUE
C
      RETURN
      END
```

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C -------------------------------------------------------------------
      SUBROUTINE DRPPRT
C
C     Written by Mark Sheldon for EER, 4/18/85
C
C     PURPOSE:
C        DRPPRT (DRoPlet PRinTout) prints variables from subroutines
C        DROP and SPRAY.
C
C        COMMON VARIABLES FROM MAIN PROGRAM
C
      LOGICAL*1 CASE(80)
C
C        COMMON VARIABLES FROMUBROUTINE SETINJ
C
      INTEGER RMAX,XMAX ,RMAXP,XMAXP
      LOGICAL*1 INCASE
      PARAMETER (RMAX=15,XMAX=25,RMAXP=16,XMAXP=26)
C
C        COMMON VARIABLES FROM SUBROUTINE SPRAY
C
      REAL LDINIT
C
      COMMON/DROPCB/
     1         XPOLD, YPOLD, UPOLD, VPOLD, VINIT, SPACE, C, XPINIT
     2         , RNDNUM, SDINIT, JRAND, LDINIT, DPOLD, TPOLD
     3       , DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/PRTCB/
     1         CASE, INCASE(80), IOUT(10)
     2         ,NPRT1, NPRT2
C
C        DEBUG OUTPUT HEADER
C
      WRITE(2,110)(CASE(I),I=1,70)
110   FORMAT(1X,/,1X,70A1)
C
      WRITE(2,120)(INCASE(I),I=1,70)
120   FORMAT(1X,70A1)
C
      IF(IOUT(6).EQ.1)WRITE(2,125)
125   FORMAT(1X,/,1X,'GRAVITY INCLUDED IN THE POSITIVE X DIRECTION')
C
      WRITE(2,220)
220   FORMAT(1X,/,1X,'DROPLET INITIAL CONDITIONS:')
C
      WRITE(2,230) DINIT
230   FORMAT(4X,'INITIAL DROP DIAMETER (M) = ',E10.3)
C
      WRITE(2,240) XPOLD,YPOLD
240   FORMAT(4X,'INITIAL POSITION: X (M)  =',F10.3,' Y (M)  =',F10.3)
C
      WRITE(2,250) UPOLD, VPOLD
250   FORMAT(4X,'INITIAL VELOCITY: U (M/S)=',F10.3,' V (M/S)=',F10.3)
C
```

```
      WRITE(2,260) LDINIT
260   FORMAT (4X,'INITIAL L/D             = ',F10.2)
C
      WRITE(2,270) SDINIT
270   FORMAT (4X;'INITIAL SPACING BETWEEN DROPLETS (M) = ',E10.3)
C
      WRITE(2,280) RNDNUM
280   FORMAT(4X,'RANDOM NUMBER FOR STATISTICAL INJECT, RNDNUM= ',F7.4,/)
C
      WRITE(2,290)
290   FORMAT(1X,'DROP TIME HISTORY')
C
      WRITE(2,310)
310   FORMAT(' ',/,' ','      STEP          POSITION (M)  VELOCITY'
     1              ,' (M/S)  LIQ   DIAM-    MASS')
C
      WRITE(2,320)
320   FORMAT(' ',' ZONE  # IN   TIME    AXIAL  RADIAL  AXIAL RADIAL'
     1          ,'  TEMP    ETER    FRAC')
C
      WRITE(2,330)
330   FORMAT(1X,'I   J  ZONE   (SEC)     X       Y       U      V'
     1          ,'       (K)    (MU)    EVAP')
C
      RETURN
      END
```

(filename: DROP3D.DAT)

```
TYPE C FLAME - EXPERIMENTAL RESULTS
IX:  20 IY :  13 IZ :        1
XL(1-5)         :   0.0100   0.0100   0.0100   0.0100   0.0100
XL(6-10)        :   0.0100   0.0100   0.0100   0.0100   0.0100
XL(11-15)       :   0.0200   0.0200   0.0200   0.0200   0.0300
XL(16-20)       :   0.0400   0.0500   0.0600   0.1100   0.2300
R(1-5)            :   0.0100   0.0100   0.0100   0.0100   0.0100
R(6-10)         :   0.0100   0.0100   0.0100   0.0100   0.0300
R(11-13)        :   0.0300   0.0500   0.0500
DTHETA(1)       : 360.0000
FCO2 : 0.1179  FH2O: 0.0965  FN2 : 0.7341  FO2 : 0.0515
AXIAL VELOCITY: INPUT BY ROWS I=1,IXPLUS, COLUMNS J=1,IY, LEVEL K=1,IZ
   0.0000  0.0000 25.0000 28.0000 15.0000  0.0000  0.0000  0.0000
   0.0000  0.0000  0.0000  0.0000  0.0000
  -5.0000  0.0000 10.0000 26.0000 20.0000  5.0000  0.0000  0.0000
   0.0000  0.0000  0.0000  0.0000  0.0000
  -5.0000 -5.0000  5.0000 20.0000 20.0000 10.0000  4.0000  0.0000
   0.0000  0.0000  0.0000  0.0000  0.0000
  -6.0000 -5.0000  2.0000 15.0000 22.0000 15.0000  8.0000  0.0000
   0.0000 -1.0000  0.0000  0.0000  0.0000
  -6.0000 -5.0000  0.0000 15.0000 25.0000 18.0000 10.0000  0.0000
   0.0000 -1.0000 -1.0000  0.0000  0.0000
  -6.0000 -5.0000  0.0000 13.0000 25.0000 24.0000 14.0000  2.0000
   0.0000 -2.0000 -2.0000  0.0000  0.0000
  -6.0000 -5.0000  1.0000  9.0000 22.0000 24.0000 15.0000  5.0000
   0.0000 -2.0000 -2.0000  0.0000  0.0000
  -5.0000 -4.0000  2.0000  8.0000 19.0000 24.0000 18.0000  8.0000
   1.0000 -2.0000 -3.0000  0.0000  0.0000
  -5.0000 -2.0000  2.0000  8.0000 15.0000 22.0000 20.0000  9.0000
   2.0000 -2.0000 -3.0000  0.0000  0.0000
  -4.0000 -2.0000  3.0000  9.0000 14.0000 17.0000 17.0000 10.0000
   3.0000 -1.0000 -3.0000  0.0000  0.0000
  -2.0000  0.0000  5.0000 10.0000 13.0000 15.0000 17.0000 13.0000
   5.0000 -1.0000 -4.0000  0.0000  0.0000
   3.0000  5.0000  9.0000 11.0000 13.0000 14.0000 15.0000 13.0000
   5.0000 -1.0000 -4.0000  0.0000  0.0000
   5.0000  8.0000 11.0000 12.0000 13.0000 14.0000 14.0000 13.0000
   5.0000  0.0000 -5.0000  0.0000  0.0000
  10.0000 10.0000 11.0000 12.0000 13.0000 13.0000 13.0000 12.0000
   6.0000  0.0000 -5.0000  0.0000  0.0000
  11.0000 11.0000 12.0000 12.0000 13.0000 13.0000 12.0000 11.0000
   7.0000  0.0000 -3.0000 -1.0000  0.0000
  10.0000 10.0000 11.0000 11.0000 11.0000 10.0000  9.0000  8.0000
   6.0000  0.0000 -1.0000 -1.0000  0.0000
   9.0000  9.0000 10.0000 10.0000  9.0000  8.0000  7.0000  6.0000
   5.0000  2.0000 -1.0000 -1.0000  0.0000
   8.0000  8.0000  8.0000  7.0000  6.0000  6.0000  5.0000  5.0000
   4.0000  3.0000  0.0000 -1.0000  0.0000
   6.0000  6.0000  5.0000  5.0000  5.0000  4.0000  4.0000  3.0000
   3.0000  2.0000  0.0000  0.0000  0.0000
   4.0000  4.0000  4.0000  4.0000  3.0000  3.0000  3.0000  3.0000
   2.0000  2.0000  1.0000  0.0000  0.0000
   2.0000  2.0000  2.0000  2.0000  2.0000  2.0000  2.0000  1.0000
   1.0000  1.0000  1.0000  1.0000  0.0000
RADIAL VELOCITY: INPUT BY ROWS I=1,IX, COLUMNS J=1,IYPLUS, LEVEL K=1,IZ
```

```
  0.0000   5.0000   5.0000   5.0000   1.0000  -1.0000  -1.0000  -2.0000
 -3.0000  -5.0000  -6.0000  -6.0000  -5.0000   0.0000
  0.0000   5.0000   5.0000   5.0000   5.0000  -1.0000  -1.0000  -2.0000
 -3.0000  -5.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   0.0000  -1.0000  -2.0000
 -3.0000  -5.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   0.0000   0.0000  -2.0000
 -3.0000  -5.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   2.0000   0.0000  -1.0000
 -2.0000  -5.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   3.0000   0.0000  -1.0000
 -2.0000  -4.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   4.0000   0.0000  -1.0000
 -2.0000  -4.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   5.0000   2.0000  -1.0000
 -2.0000  -2.0000  -6.0000  -6.0000  -4.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   6.0000   5.0000   3.0000   0.0000
 -1.0000  -3.0000  -6.0000  -5.0000  -4.0000   0.0000
  0.0000   6.0000   6.0000   6.0000   6.0000   5.0000   3.0000   0.0000
 -1.0000  -3.0000  -6.0000  -5.0000  -4.0000   0.0000
  0.0000   6.0000   6.0000   7.0000   6.0000   5.0000   3.0000   0.0000
 -1.0000  -3.0000  -5.0000  -5.0000  -3.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   6.0000   5.0000   3.0000   0.0000
 -1.0000  -3.0000  -5.0000  -5.0000  -3.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   6.0000   5.0000   4.0000   2.0000
  0.0000  -3.0000  -5.0000  -5.0000  -3.0000   0.0000
  0.0000   5.0000   6.0000   6.0000   5.0000   5.0000   4.0000   2.0000
  0.0000  -2.0000  -5.0000  -4.0000  -3.0000   0.0000
  0.0000   5.0000   5.0000   5.0000   5.0000   4.0000   4.0000   3.0000
  1.0000  -1.0000  -4.0000  -4.0000  -3.0000   0.0000
  0.0000   5.0000   5.0000   5.0000   5.0000   4.0000   3.0000   2.0000
  2.0000  -1.0000  -3.0000  -3.0000  -3.0000   0.0000
  0.0000   4.0000   4.0000   5.0000   4.0000   4.0000   3.0000   3.0000
  2.0000  -1.0000  -2.0000  -2.0000  -2.0000   0.0000
  0.0000   2.0000   3.0000   3.0000   3.0000   3.0000   2.0000   2.0000
  1.0000   0.0000  -1.0000  -2.0000  -2.0000   0.0000
  0.0000   1.0000   1.0000   2.0000   2.0000   2.0000   2.0000   1.0000
  1.0000   0.0000  -1.0000  -1.0000  -1.0000   0.0000
  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
TANGENTIAL VELOCITY: INPUT BY ROWS I=1,IX, COLUMNS J=1,IY, LEVEL K=1,2
  0.      -10.0000-12.0000-11.0000 -8.0000 -5.0000 -4.0000 -3.0000
 -3.        -3.0000 -3.0000 -3.0000 -2.0000
  0.0000-10.0000-12.00C0-12.0000-11.0000 -7.0000 -5.0000 -4.0000
 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000-10.0000-12.0000-12.0000-11.0000-10.0000 -8.0000 -5.0000
 -4.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000-10.0000-11.0000-12.0000-12.0000-11.0000 -9.0000 -7.0000
 -5.0000 -4.0000 -3.0000 -3.0000 -3.0000
  0.0000 -9.0000-11.0000-12.0000-12.0000-11.0000-10.0000 -8.0000
 -6.0000 -4.0000 -3.0000 -3.0000 -3.0000
  0.0000 -7.0000-10.0000-11.0000-12.0000-11.0000-11.0000-10.0000
 -8.0000 -5.0000 -4.0000 -3.0000 -3.0000
  0.0000 -6.0000 -8.0000-11.0000-11.0000-11.0000-11.0000-11.0000
 -9.0000 -6.0000 -4.0000 -3.0000 -3.0000
```

```
  0.0000 -5.0000 -8.0000-10.0000-11.0000-11.0000-11.0000-11.0000
-10.0000 -7.0000 -4.0000 -4.0000 -3.0000
  0.0000 -5.0000 -7.0000 -9.0000-10.0000-11.0000-11.0000-11.0000
-10.0000 -8.0000 -5.0000 -4.0000 -3.0000
  0.0000 -4.0000 -6.0000 -8.0000 -9.0000-10.0000-11.0000-11.0000
-11.0000 -8.0000 -5.0000 -4.0000 -3.0000
  0.0000 -4.0000 -5.0000 -7.0000 -8.0000-10.0000-10.0000-10.0000
-10.0000 -9.0000 -6.0000 -4.0000 -3.0000
  0.0000 -4.0000 -5.0000 -6.0000 -6.0000 -8.0000 -9.0000 -9.0000
-10.0000 -9.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -5.0000 -5.0000 -6.0000 -7.0000 -8.0000
 -8.0000 -9.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -4.0000 -4.0000 -5.0000 -6.0000 -7.0000
 -7.0000 -8.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -4.0000 -4.0000 -5.0000 -5.0000 -6.0000
 -6.0000 -7.0000 -7.0000 -6.0000 -4.0000
  0.0000 -3.0000 -3.0000 -4.0000 -4.0000 -4.0000 -4.0000 -5.0000
 -5.0000 -6.0000 -6.0000 -6.0000 -4.0000
  0.0000 -2.0000 -3.0000 -3.0000 -3.0000 -4.0000 -4.0000 -4.0000
 -4.0000 -5.0000 -5.0000 -5.0000 -5.0000
  0.0000 -2.0000 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000 -4.0000
 -4.0000 -4.0000 -4.0000 -4.0000 -4.0000
  0.0000 -2.0000 -2.0000 -2.0000 -3.0000 -3.0000 -3.0000 -3.0000
 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000
 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000
  0.      -10.0000-12.0000-11.0000 -8.0000 -5.0000 -4.0000 -3.0000
 -3.        -3.0000 -3.0000 -3.0000 -2.0000
  0.0000-10.0000-12.0000-12.0000-11.0000 -7.0000 -5.0000 -4.0000
 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000-10.0000-12.0000-12.0000-11.0000-10.0000 -8.0000 -5.0000
 -4.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000-10.0000-11.0000-12.0000-12.0000-11.0000 -9.0000 -7.0000
 -5.0000 -4.0000 -3.0000 -3.0000 -3.0000
  0.0000 -9.0000-11.0000-12.0000-12.0000-11.0000-10.0000 -8.0000
 -6.0000 -4.0000 -3.0000 -3.0000 -3.0000
  0.0000 -7.0000-10.0000-11.0000-12.0000-11.0000-11.0000-10.0000
 -8.0000 -5.0000 -4.0000 -3.0000 -3.0000
  0.0000 -6.0000 -8.0000-11.0000-11.0000-11.0000-11.0000-11.0000
 -9.0000 -6.0000 -4.0000 -3.0000 -3.0000
  0.0000 -5.0000 -8.0000-10.0000-11.0000-11.0000-11.0000-11.0000
-10.0000 -7.0000 -4.0000 -4.0000 -3.0000
  0.0000 -5.0000 -7.0000 -9.0000-10.0000-11.0000-11.0000-11.0000
-10.0000 -8.0000 -5.0000 -4.0000 -3.0000
  0.0000 -4.0000 -6.0000 -8.0000 -9.0000-10.0000-11.0000-11.0000
-11.0000 -8.0000 -5.0000 -4.0000 -3.0000
  0.0000 -4.0000 -5.0000 -7.0000 -8.0000-10.0000-10.0000-10.0000
-10.0000 -9.0000 -6.0000 -4.0000 -3.0000
  0.0000 -4.0000 -5.0000 -6.0000 -6.0000 -8.0000 -9.0000 -9.0000
-10.0000 -9.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -5.0000 -5.0000 -6.0000 -7.0000 -8.0000
 -8.0000 -9.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -4.0000 -4.0000 -5.0000 -6.0000 -7.0000
 -7.0000 -8.0000 -7.0000 -5.0000 -4.0000
  0.0000 -3.0000 -4.0000 -4.0000 -4.0000 -5.0000 -5.0000 -6.0000
 -6.0000 -7.0000 -7.0000 -6.0000 -4.0000
  0.0000 -3.0000 -3.0000 -4.0000 -4.0000 -4.0000 -4.0000 -5.0000
 -5.0000 -6.0000 -6.0000 -6.0000 -4.0000
  0.0000 -2.0000 -3.0000 -3.0000 -3.0000 -4.0000 -4.0000 -4.0000
 -4.0000 -5.0000 -5.0000 -5.0000 -5.0000
  0.0000 -2.0000 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000 -4.0000
 -4.0000 -4.0000 -4.0000 -4.0000 -4.0000
  0.0000 -2.0000 -2.0000 -2.0000 -3.0000 -3.0000 -3.0000 -3.0000
 -3.0000 -3.0000 -3.0000 -3.0000 -3.0000
  0.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000
 -2.0000 -2.0000 -2.0000 -2.0000 -2.0000
TEMP  : INPUT BY ROWS I=1,IX,                     COLUMNS J=1,IY, LEVEL K=1,IZ
 1200.00 1100.0  1100.0  1100.0  1100.0  1100.0  1095.0  1090.
 1085.0  1080.0  1080.0  1080.0  1080.0
 1425.0  1350.0  1220.0  1145.0  1125.0  1115.0  1110.0  1105.
 1105.0  1105.0  1102.0  1100.0  1085.0
 1525.0  1450.0  1300.0  1175.0  1145.0  1140.0  1135.0  1125.
 1110.0  1105.0  1105.0  1102.0  1095.0
 1580.0  1520.0  1360.0  1200.0  1175.0  1150.0  1140.0  1130.
 1125.0  1115.0  1110.0  1105.0  1100.0
 1620.0  1550.0  1400.0  1300.0  1200.0  1170.0  1145.0  1140.
 1130.0  1125.0  1115.0  1107.0  1102.0
 1650.0  1600.0  1440.0  1320.0  1230.0  1185.0  1160.0  1145.
 1140.0  1130.0  1120.0  1110.0  1104.0
 1700.0  1630.0  1460.0  1340.0  1250.0  1200.0  1175.0  1150.
 1140.0  1130.0  1125.0  1113.0  1107.0
 1720.0  1660.0  1490.0  1350.0  1270.0  1220.0  1180.0  1160.
 1145.0  1135.0  1127.0  1117.0  1110.0
 1750.0  1700.0  1500.0  1360.0  1280.0  1235.0  1185.0  1170.0
 1150.0  1140.0  1130.0  1120.0  1112.0
 1770.0  1690.0  1500.0  1380.0  1295.0  1250.0  1200.0  1175.0
 1155.0  1140.0  1130.0  1122.0  1114.0
 1710.0  1640.0  1500.0  1390.0  1300.0  1260.0  1210.0  1180.
 1170.0  1145.0  1135.0  1125.0  1116.
 1650.0  1590.0  1480.0  1395.0  1305.0  1270.0  1235.0  1200.
 1180.0  1150.0  1140.0  1128.0  1118.
 1590.0  1520.0  1460.0  1400.0  1310.0  1275.0  1250.0  1220.
 1185.0  1155.0  1140.0  1130.0  1120.0
 1525.0  1490.0  1440.0  1395.0  1305.0  1275.0  1250.0  1220.
 1195.0  1170.0  1140.0  1130.0  1122.0
 1460.0  1450.0  1410.0  1370.0  1300.0  1275.0  1255.0  1225.
 1210.0  1175.0  1145.0  1135.0  1125.0
 1410.0  1400.0  1390.0  1325.0  1295.0  1275.0  1255.0  1240.
 1220.0  1190.0  1150.0  1140.0  1130.0
 1360.0  1350.0  1325.0  1300.0  1290.0  1275.0  1255.0  1240.
 1225.0  1200.0  1170.0  1145.0  1135.0
 1320.0  1310.0  1295.0  1295.0  1280.0  1270.0  1255.0  1240.
 1225.0  1210.0  1180.0  1155.0  1142.0
 1285.0  1280.0  1280.0  1280.0  1270.0  1265.0  1255.0  1245.
 1235.0  1225.0  1200.0  1175.0  1155.0
 1260.0  1260.0  1260.0  1260.0  1255.0  1250.0  1245.0  1240.
 1230.0  1215.0  1205.0  1190.0  1165.0
  DROPLET COMPOSITION: 80% XYLENE, 20% FUEL OIL
TINIT  :  298.0
TBL1   :  430.0    TBL2   :  523.0    TBL3   :  800.0
```

```
DRT2     :     0.150  DRT3     :     0.0132 DRT4     :     0.0000
CPLIQ1  : 1720.0     CPLIQ2  : 1890.0     CPLIQ3  : 1920.0
LHELIQ1: 3.350E+05 LHELIQ2: 2.700E+05
RHOLIQ1:  870.0     RHOLIQ2:  880.0     RHOLIQ3: 1500.0
HCOMLQ1: 4.310E+07 HCOMLQ2: 4.230E+07
AFMRAT1:     3.135  AFMRAT2:     3.125  AFMRAT3:     1.333
XNOZ     :     0.0    YNOZ     :     0.1400 ZNOZ     :     0.0
ZSAFE    :     0.2000 DSAFE    :     0.2000
TSAFE    :     0.2000 ESAFE    :     0.2000
TOL1     :     0.0001 NRAMP    :         30
MAXSTP   :       5000 NDROP    :          1
NPRT1    :          1 NPRT2    :         50
NPRT3    :          2
INJOUT1:            0 INJOUT2:            0
INJOUT3:            1 INJOUT4:            1
INJOUT5:            0 INJOUT6:            0
INJOUT7:            0 INJOUT8:            0
INJOUT9:            0 INJOUT0:            0
INPTYP1:            0 INPTYP2:            0
INPTYP3:            0 INPTYP4:            0
INPTYP5:            0 INPTYP6:            0
INPTYP7:            1 INPTYP8:            0
TWDUM    :   298.0    TGDUM    :   300.0
UDUM     :     0.0000 VDUM     :     0.0000
SWIRL    :     0.0    TOTLEN   :     0.9144
JLAYER   :          0 JFORCE   :          1
TIMAX    :         25
TBTS     : 5.000E-02
TRNO     :     0.1000
XSIGMA   :     5.0000 YSIGMA   :     7.5000 ZSIGMA   :     5.0000
DINIT    : 0.234E-03
DRPVEL   :     6.2200
XPCOMP   :+    0.8660
YPCOMP   :  -  0.5000
ZPCOMP   :     0.0000
L/D      :   131.0
DINIT    :+0.234E-03
DRPVEL   :     7.7100
XPCOMP   :+    0.8660
YPCOMP   :  -  0.5000
ZPCOMP   :     0.0000
L/D      :     2.54
DINIT    : 0.234E-03
DRPVEL   :     7.2700
XPCOMP   :+    0.8660
YPCOMP   :  -  0.5000
ZPCOMP   :     0.0000
L/D      :     4.79
DINIT    : 0.234E-03
DRPVEL   :     6.9100
XPCOMP   :+    0.8660
YPCOMP   :  -  0.5000
ZPCOMP   :     0.0000
L/D      :     9.10
DINIT    : 0.234E-03
```

```
DRPVEL :     6.6300
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :   17.5
DINIT  : 0.234E-03
DRPVEL :     6.4300
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :   33.9
DINIT  : 0.306E-03
DRPVEL :     7.9100
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  127.0
DINIT  : 0.371E-03
DRPVEL :     7.8200
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  104.0
DINIT  : 0.306E-03
DRPVEL :     7.3200
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  118.0
DINIT  : 0.376E-03
DRPVEL :     8.7700
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  120.0
DINIT  : 0.205E-03
DRPVEL :     3.8100
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :   91.7
DINIT  : 0.255E-03
DRPVEL :     7.3900
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  142.0
DINIT  : 0.216E-03
DRPVEL :     3.6000
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :   96.9
DINIT  : 0.255E-03
DRPVEL :     7.8500
```

```
XPCOMP :+   0.8660
YPCOMP :  - 0.5000
ZPCOMP :    0.0000
L/D    :  151.0
DINIT  : 0.239E-03
DRPVEL :    7.3600
XPCOMP :+   1.0000
YPCOMP :  - 0.0000
ZPCOMP :    0.0000
L/D    :    2.54
DINIT  : 0.239E-03
DRPVEL :    5.9800
XPCOMP :+   1.0000
YPCOMP :  - 0.0000
ZPCOMP :    0.0000
L/D    :  132.0
DINIT  : 0.234E-03
DRPVEL :    5.3800
XPCOMP :+   0.7071
YPCOMP :  - 0.7071
ZPCOMP :    0.0000
L/D    :  113.0
DINIT  : 0.234E-03
DRPVEL :    6.2200
XPCOMP :+   0.7071
YPCOMP :  - 0.7071
ZPCOMP :    0.0000
L/D    :  131.0
```

```
XPCOMP :+    0.8660
YPCOMP :   - 0.5000
ZPCOMP :     0.0000
L/D    :   151.0
DINIT  : 0.239E-03
DRPVEL :     7.3600
XPCOMP :+    1.0000
YPCOMP :   - 0.0000
ZPCOMP :     0.0000
L/D    :     2.54
DINIT  : 0.239E-03
DRPVEL :     5.9800
XPCOMP :+    1.0000
YPCOMP :   - 0.0000
ZPCOMP :     0.0000
L/D    :   132.0
DINIT  : 0.234E-03
DRPVEL :     5.3800
XPCOMP :+    0.7071
YPCOMP :   - 0.7071
ZPCOMP :     0.0000
L/D    :   113.0
DINIT  : 0.234E-03
DRPVEL :     6.2200
XPCOMP :+    0.7071
YPCOMP :   - 0.7071
ZPCOMP :     0.0000
L/D    :   131.0
```

```
          (filename:  DROP3D1.FOR)
C                                      3DTFDBM
C       PROGRAM 3DTFDBM
C
C       Written by Wyman Clark, modified by Mark Sheldon 4/30/85
C       Modified by Susan Robinson, 6/9/87
C       Modified by Jim Mulholland, 7/10/87
C
C           "3DTFDBM" stands for:
C           "Three-Dimensional Turbulent Flame Droplet Ballistics Model"
C
C***** DECLARATIONS
C
             LOGICAL*1 LABEL(70,10)
             INTEGER     TIMAX
             LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
        COMMON/DIMCB/
       1          IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
        COMMON/PRTCB/
       1          CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
       2         ,NPRT1 , NPRT2 , NPRT3
C
        COMMON/INPUT/
       1                V(25,15,5),   TEMP(25,15,5)
       2         ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
       3         ,II    , JI    , KI    , NCMPND, COMPND, JRAND
       4        ,XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
        COMMON/BDYCB/
       1          XL(25)    , XBDY(26)  , UBDY(26,15,5), UBDY1(26,15,5)
       2         ,R(15)     , YBDY(16)  , VBDY(25,16,5), VBDY1(25,16,5)
       3         ,DTHETA(5) , ZBDY(6)   , WBDY(25,15,6), WBDY1(25,15,6)
       4         ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
        COMMON/GASCB/
       1          CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
       2         ,FO2   , FN2   , FCO2  , FH2O
C
C***** END OF DECLARATIONS
C
        OPEN(UNIT=5,FILE='DROP3D.DAT')
C
C        INPUT TEST CONDITIONS:
C                           CASE NAME,CASE
C                           NUMBER OF ZONES PER COORDINATE: IX,IY,IZ
C                           ZONE DIMENSIONS: XL, R, DTHETA
C                           MASS FRACTION (WET, ASH) CO2,H2O,N2,O2
C                           RELATIVE MASS FLOWS,MDOTxx (INPUT=1 BASIS)
C                           ZONE GAS TEMPERATURES,TEMP
C
C       CASE TITLE
C
        READ(5,100)(CASE(I),I=1,60)
 100    FORMAT(80A1)
```

```
C
C     ARRAY DIMENSIONS
C
      READ(5,200)IX,IY,IZ
200   FORMAT(3X,3(I4,5X))
C
C     ZONE DIMENSIONS AND VOLUMES
C
      I1 = 1
      I2 = 5
      DO 310 L = 1,IX
         IF(IX.LT.I2) I2 = IX
         READ(5,320)(XL(I),I=I1,I2)
320      FORMAT(15X,5(1X,F8.4))
         I1 = I2 + 1
         I2 = I1 + 4
         IF(I1.GT.IX) GOTO 340
310   CONTINUE
340   CONTINUE
C
      I1 = 1
      I2 = 5
      DO 350 L = 1,IY
         IF(IY.LT.I2) I2 = IY
         READ(5,320)(R(J),J=I1,I2)
         I1 = I2 + 1
         I2 = I1 + 4
         IF(I1.GT.IY) GOTO 370
350   CONTINUE
370   CONTINUE
C
      I1 = 1
      I2 = 5
      DO 380 L = 1,IZ
         IF(IZ.LT.I2) I2 = IZ
         READ(5,320)(DTHETA(K),K=I1,I2)
         I1 = I2 + 1
         I2 = I1 + 4
         IF(I1.GT.IZ) GOTO 400
380   CONTINUE
400   CONTINUE
C
C     MASS FLOWRATE AND MASS FRACTIONS
C
      READ(5,520)FCO2,FH2O,FN2,FO2
520   FORMAT(4(6X,F8.5))
C
      SUMASS=(FCO2/.044)+(FH2O/.018)+(FN2/.028)+(FO2/.032)
C
C     VELOCITIES IN THE AXIAL DIRECTION
C
      IXPLUS = IX+1
      READ(5,100)(LABEL(I,1),I=1,70)
      DO 610 I=1,IXPLUS
          I1=1
         I2=8
         DO 620 L=1,IX
           IF(IY.LT.I2) I2=IY
           READ(5,600)(UBDY1(I,J,1),J=I1,I2)
 600  FORMAT(8F8.4)
           I1=I2+1
           I2=I1+7
           IF(I1.GT.IY) GO TO 610
 620     CONTINUE
 610   CONTINUE
C
C     VELOCITIES IN THE RADIAL DIRECTION
C
       IYPLUS=IY+1
       READ(5,100)(LABEL(I,2),I=1,70)
       DO 630 I=1,IX
         I1=1
         I2=8
         DO 640 L=1,IX
           IF(IYPLUS.LT.I2) I2=IYPLUS
           READ(5,625) (VBDY1(I,J,1),J=I1,I2)
 625  FORMAT(8F8.4)
           I1=I2+1
           I2=I1+7
           IF(I1.GT.IYPLUS) GO TO 632
 640     CONTINUE
 632   CONTINUE
 630   CONTINUE
C
      IZPLUS=IZ+1
      READ(5,100)(LABEL(I,6),I=1,70)
      DO 690 K = 1,IZPLUS
      DO 700 I = 1,IX
         I1=1
         I2=8
         DO 710 L=1,IX
           IF(IY.LT.I2) I2=IY
           READ(5,600)(WBDY1(I,J,K),J=I1,I2)
           I1=I2+1
           I2=I1+7
           IF(I1.GT.IY) GO TO 700
 710       CONTINUE
 700     CONTINUE
 690   CONTINUE
C
C     GAS TEMPERATURES
C
      READ(5,100)(LABEL(I,7),I=1,70)
      DO 910 K=1,IZ
      DO 910 I=1,IX
        I1=1
        I2=8
        DO 925 L=1,IY
        IF(IY.LT.I2) I2=IY
        READ(5,920)(TEMP(I,J,K),J=I1,I2)
```

```
920      FORMAT(8F8.2)
         I1=I2+1
         I2=I1+7
         IF(I1.GT.IY) GO TO 915
925    CONTINUE  -
915    CONTINUE
910   CONTINUE
C
C     CONCLUDE INPUT AND CALL INJECTION MODEL
C
      CALL ICSINJ
      CLOSE(UNIT=5)
      STOP
      END
C ----------------------------------------------------------------------
      SUBROUTINE ICSINJ
C
C     Modified from INJECT by Mark Sheldon for EER, 4/30/85
C
C     PURPOSE: "ICSINJ" stands for:
C         "Incineration Cylindrical 3-d model,
C           Subroutine for INJection"
C
C     SUBROUTINES CALLED BY ICSINJ    (SOME INDIRECTLY):
C         ICSSET     Calculates data (except gas prop) for other routines
C         ICSGAS     Calculates gas properties ( Cp, Visc, Therm. Cond.)
C         ICSDRP     Sends droplet through incinerator, zozone by zone
C         ICSSPR     Gives initial conditions to each droplet
C         ICSMOV     Trajectory/heating/evaporation of drop in 1 timestep
C         ICPSET     Output header from ICSINJ
C         ICPGAS     Output header from ICSGAS
C         ICPSPR     Output header from ICSDRP and/or ICSSPR
C         ICPINJ     Output header from ICSINJ (final results)
C       RANDOM
C       INS5
C       ARRPRT
C       ICSTTS   Calculates turbulent time scale gas velocity
C
          REAL         LHELIQ, LHELIQ1, LHELIQ2
            INTEGER     TIMAX, DSTMAX, DSTRIB
            LOGICAL*1   COMPND(40,20), CASE(60), INCASE
            LOGICAL     BOIL, CNVRG, GETOUT
C
       COMMON/DIMCB/
     1         IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
       COMMON/LIQCB/
     1         TLIQ, TINIT, IDUM
     2       , TBOIL, TBL1, TBL2, TBL3
     3       , DRT2, DRT3, DRT4, DRT3I
     4       , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5       , LHELIQ, LHELIQ1, LHELIQ2
     6       , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7       , HCOMLQ, HCOMLQ1, HCOMLQ2
     8       , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
```

```
C
      COMMON/PARMCB/
     1          ZSAFE , DSAFE , TSAFE , ESAFE , TOL1
     2         ,NDROP , MAXSTP, NRAMP
C
      COMMON/PRTCB/
     1          CASE  , INCASE(80)     , INJOUT(10), INPTYP(10)
     2         ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/MOVECB/
     1          DTIME , DTSAV , OLDDT , TIME  , PATH  , DIAM
     2         ,UGAS  , VGAS  , WGAS  , IINEW , JINEW , KINEW
     3         ,ICNT1 , ICNT2 , PRANDT, BOIL  , CNVRG , GETOUT
     4       ,ITBTS
C
      COMMON/INPUT/
     1               V(25,15,5),   TEMP(25,15,5)
     2         ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3         ,II    , JI    , KI    , NCMPND, COMPND, JRAND
     4       ,XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/BDYCB/
     1          XL(25)    , XBDY(26)  , UBDY(26,15,5), UBDY1(26,15,5)
     2         ,R(15)     , YBDY(16)  , VBDY(25,16,5), VBDY1(25,16,5)
     3         ,DTHETA(5) , ZBDY(6)   , WBDY(25,15,6), WBDY1(25,15,6)
     4         ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
      COMMON/GASCB/
     1          CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
     2         ,FO2   , FN2   , FCO2  , FH20
C
      COMMON/DROPCB/
     1          XPOLD, YPOLD, ZPOLD, UPOLD, VPOLD, WPOLD, DRPVEL
     2         ,XPINIT, YPINIT, ZPINIT, UPINIT, VPINIT, WPINIT
     3         ,RNDNUM, SPACIN, C, SPACE, IT, LOD, VINIT1
     4         ,DPOLD, TPOLD, DINIT, DINIT2, DINIT3, DINIT4
C
       COMMON/PRINT/
     1          DSTRIB(50,20), DSTMAX, NXMAX, NYMAX, XMEAN, YMEAN, ZMEAN
     2          , XFINAL, YFINAL, NXGRID, NYGRID, STDVX, STDVY, STDVZ
     3          , XMAX, YMAX, ZMAX, XMIN, YMIN, ZMIN
C
      COMMON/NOZCB/
     1        XNOZ,YNOZ,ZNOZ
     2        ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
C     DATA INITIALIZATION
C
C     OUTPUT FILE
C
      OPEN(UNIT=7,FILE='STAT.OUT')
      OPEN(UNIT=8,FILE='DROP3D.OUT')
C
C     SET INCINERATOR CONDITIONS
C
```

```
      CALL ICSSET
      CALL ICSGAS
C
C     INJECT DROPS AND TALLY THE ENDPOINT DISTRIBUTION
C
      IF(INJOUT(3).EQ.1) INJFL3 = 1
      DO 3000 M = 1,NDROP
      WRITE(6,300)M
      WRITE(7,300)M
      WRITE(8,300)M
300   FORMAT(// 1X,'DROP NO. ',I4,2X,'****************************'
     1       ,'************************'/)
C
      XSUM = 0
      YSUM = 0
      ZSUM = 0
      XSQSUM = 0
      YSQSUM = 0
      ZSQSUM = 0
      DO 10 I=1,20
      DO 10 J=1,20
      DSTRIB(I,J) = 0
 10   CONTINUE
      IF (INJFL3.EQ.1) INJOUT(3) = 1
C
      IF(INPTYP(6).EQ.1.AND.INJOUT(9).EQ.0) GO TO 1100
      DO 1000 IT = 1,TIMAX
          IF(IT.GT.NPRT3) INJOUT(3)=0
        ITBTS = 1
C
      DO 500 I = 1,IX
      DO 510 J = 1,IY
      DO 520 K = 1,IZ
      UBDY(I,J,K) = UBDY1(I,J,K)
      VBDY(I,J,K) = VBDY1(I,J,K)
      WBDY(I,J,K) = WBDY1(I,J,K)
520   CONTINUE
510   CONTINUE
500   CONTINUE
C
C     CHANGE GAS VELOCITIES TO FIT TURBULENT DISTRIBUTION
C
        IF(INPTYP(6).EQ.0) CALL ICSTTS
C
          CALL ICSDRP
C
      IF(TIMAX.EQ.1) GO TO 4000
C
      XSUM = XSUM + XPOLD
      YSUM = YSUM + YPOLD
      ZSUM = ZSUM + ZPOLD
      XSQSUM = XSQSUM + XPOLD **2
      YSQSUM = YSQSUM + YPOLD **2
      ZSQSUM = ZSQSUM + ZPOLD **2
      IF (XPOLD.GT.XMAX) XMAX = XPOLD
      IF (YPOLD.GT.YMAX) YMAX = YPOLD
      IF (ZPOLD.GT.ZMAX) ZMAX = ZPOLD
      IF (XPOLD.LT.XMIN) XMIN = XPOLD
      IF (YPOLD.LT.YMIN) YMIN = YPOLD
      IF (ZPOLD.LT.ZMIN) ZMIN = ZPOLD
      IF (IT.LT.TIMAX) GO TO 200
C
C     STATISTICAL CALCULATIONS
C
          XMEAN = XSUM/TIMAX
          YMEAN = YSUM/TIMAX
          ZMEAN = ZSUM/TIMAX
          STDVX = SQRT(ABS((XSQSUM * TIMAX - XSUM**2)/TIMAX/(TIMAX-1)))
          STDVY = SQRT(ABS((YSQSUM * TIMAX - YSUM**2)/TIMAX/(TIMAX-1)))
          STDVZ = SQRT(ABS((ZSQSUM * TIMAX - ZSUM**2)/TIMAX/(TIMAX-1)))
C
200   IF(IT.GE.2) GO TO 101
       XFINAL = XPOLD
       YFINAL = YPOLD
       ZFINAL = ZPOLD
       XMIN = XPOLD
       YMIN = YPOLD
       ZMIN = ZPOLD
       XMAX = XPOLD
       YMAX = YPOLD
       ZMAX = ZPOLD
       INTX = INT(XPOLD * 100.)
       INTY = INT(YPOLD * 100.)
       NXGRID = 10
       NYGRID = 6
          IF(INTX.LT.15) NXGRID = INTX
          IF(INTY.LT.5) NYGRID = INTY
C
C     TALLY LOCATION OF X COORDINATE IN FINAL GRID
C
 101  IF(XPOLD.GE.XFINAL) GO TO 103
         IADDX = INT(INTX - XPOLD * 100.) + 1
         NX = NXGRID - IADDX
         IF (NX.GE.1) GO TO 102
          NXA = IABS(NX) + 1
          NXMAXP = NXMAX + NXA
          NXAP = NXA + 1
          NDIF = NXMAXP - NXAP
          DO 1 JI = 1,NDIF
           I = NXMAXP - JI
           IDUM = I - NXA
           DO 1 J = 1,NYMAX
           DSTRIB(I,J) = DSTRIB(IDUM,J)
           DSTRIB(IDUM,J) = 0
   1      CONTINUE
           NX = 1
           NXMAX = NXMAXP
           NXGRID = NXGRID + NXA
     GO TO 102
 103     IADDX = INT(XPOLD*100. - INTX)
```

```
            NX = NXGRID + IADDX
            IF (NX.GT.NXMAX) NXMAX = NX
C
C      TALLY LOCATION OF Y COORDINATE IN FINAL GRID
C
 102  IF(YPOLD.GE.YFINAL) GO TO 105
            IADDY = INT(INTY - YPOLD * 100.) + 1
            NY = NYGRID - IADDY
            IF(NY.GE.1) GO TO 104
C
C           SHIFT ENTIRE GRID AND PREVIOUSLY COUNTED POINTS
C
               NYA = IABS(NY) + 1
               NYMAXP = NYMAX + NYA
               NYAP = NYA + 1
               NDIF = NYMAXP - NYAP
               DO 2 JI=1,NDIF
               J = NYMAXP - JI
               IDUM = J - NYA
               DO 2 I = 1,NXMAX
               DSTRIB(I,J) = DSTRIB(I,IDUM)
               DSTRIB(I,IDUM) = 0
 2             CONTINUE
               NY = 1
               NYMAX = NYMAXP
               NYGRID = NYGRID + NYA
            GO TO 104
 105         IADDY = INT(YPOLD * 100 - INTY)
             NY = NYGRID + IADDY
             IF (NY.GT.NYMAX) NYMAX = NY
C
 104    DSTRIB(NX,NY) = DSTRIB(NX,NY) + 1
        IF (DSTRIB(NX,NY).GT.DSTMAX) DSTMAX = DSTRIB(NX,NY)
C
4000  CONTINUE
C
      WRITE(6,900) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
      WRITE(8,900) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
      WRITE(7,900) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
 900  FORMAT (3X,'AXIAL (M) =',F5.3,'  RADIAL (M) =',F5.3,
     1          '  ANGLE (DEG) =',F6.1/  3X,'DIAMETER (uM) =',F6.1,
     2        '  TEMPERATURE (K) =',F7.1,'  TIME (SEC) = ',E10.3/)
C
      IF(INPTYP(6).EQ.1) GO TO 410
      IF(INJOUT(6).EQ.2) WRITE(6,400) ITBTS
      IF(INJOUT(6).EQ.2) WRITE(7,400) ITBTS
      IF(INJOUT(6).EQ.2) WRITE(8,400) ITBTS
400   FORMAT(2X,'"RANDOM" CALLED ',I4,' TIMES'//)
410   CONTINUE
C
 1000  CONTINUE
       GO TO 2000
C
C      CASE WITH NO TURBULENCE
C
```

```
1100  CONTINUE
          IT =1
      DO 1110 I = 1,IX
      DO 1120 J = 1,IY
      DO 1130 K = 1,IZ
      UBDY(I,J,K) = UBDY1(I,J,K)
      VBDY(I,J,K) = VBDY1(I,J,K)
      WBDY(I,J,K) = WBDY1(I,J,K)
1130  CONTINUE
1120  CONTINUE
1110  CONTINUE
      INJOUT(4) = 0
      CALL ICSDRP
      WRITE(6,905) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
      WRITE(8,905) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
      WRITE(7,905) XPOLD,YPOLD,ZPOLD,DPOLD,TPOLD,TIME
 905  FORMAT (3X,'AXIAL (M) =',F5.3,'  RADIAL (M) =',F5.3,
     1          '  ANGLE (DEG) =',F6.1/  3X,'DIAMETER (uM) =',F6.1,
     2         '  TEMPERATURE (K) =',F7.1,'  TIME (SEC) = ',E10.3/)
C
2000  CONTINUE
C
C     OUTPUT RESULTS OF INJECTION MODEL
C
      IF(TIMAX.EQ.1) INJOUT(4) = 0
      IF(INJOUT(4).EQ.1) CALL ICPINJ
C
3000  CONTINUE
      CLOSE(UNIT=8)
      CLOSE(UNIT=7)
      RETURN
      END
C ------------------------------------------------------------------
      SUBROUTINE RANDOM(STDDEV,N)
C
C    THIS SUBROUTINE GENERATES RANDOM NUMBERS BETWEEN 0 AND 1000,
C    THEN INSTITUTES A GAUSSIAN DISTRIBUTION FROM THE RANDOM OUTPUT.
C    THE PRIMARY REFERENCE IS FOR THE RANDOM NUMBER GENERATOR IS:
C
C                 R. Rouse and T. Bugnitz
C                 Programming the IBM Personal Computer: Fortran 77
C                 Holt, Rhinehart, and Winston , 1983
C
      INTEGER IA(55),START1,START2
      REAL X(500)
      LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
      COMMON/INPUT/
     1             V(25,15,1),   TEMP(25,15,1)
     2        ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3        ,II    , JI    , KI    , NCMPND, COMPND, JRAND
     4      ,XSIGMA ,YSIGMA ,ZSIGMA, TBTS, TRNO
C
      COMMON/PRTCB/
     1         CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2          ,NPRT1 , NPRT2 , NPRT3
C
C      D IS RANDOM NUMBER BETWEEN 0 AND 1000
C
      CALL GETTIM -(I1,I2,I3,I4)
      START1 = ( I1 + I2 + I3 + I4 ) * 1000
      CALL IN55(IA,START1)
      JRAND = JRAND + 1
      IF (JRAND.GT.55) JRAND = IRN55(IA)
      D = FLOAT (IA(JRAND)) * 1.0E-9 * 1000
      IF(INJOUT(8).EQ.1) GO TO 100
      N = -1
      IF (D.GT.500) N = 1
      IF (D.GT.500) D = D - 500.
C
      IF(D.LT.20.9) STDDEV=0
      IF(D.GE.20.9.AND.D.LT.60.6) STDDEV = 0.1
      IF(D.GE.60.6.AND.D.LT.99.7) STDDEV = 0.2
      IF(D.GE.99.7.AND.D.LT.137.8) STDDEV = 0.3
      IF(D.GE.137.8.AND.D.LT.174.7) STDDEV = 0.4
      IF(D.GE.174.7.AND.D.LT.209.9) STDDEV = 0.5
      IF(D.GE.209.9.AND.D.LT.243.2) STDDEV = 0.6
      IF(D.GE.243.2.AND.D.LT.274.4) STDDEV = 0.7
      IF(D.GE.274.4.AND.D.LT.303.4) STDDEV = 0.8
      IF(D.GE.303.4.AND.D.LT.330.0) STDDEV = 0.9
      IF(D.GE.330.0.AND.D.LT.354.2) STDDEV = 1.0
      IF(D.GE.354.2.AND.D.LT.376.0) STDDEV = 1.1
      IF(D.GE.376.0.AND.D.LT.395.4) STDDEV = 1.2
      IF(D.GE.395.4.AND.D.LT.412.6) STDDEV = 1.3
      IF(D.GE.412.6.AND.D.LT.427.5) STDDEV = 1.4
      IF(D.GE.427.5.AND.D.LT.440.5) STDDEV = 1.5
      IF(D.GE.440.5.AND.D.LT.451.6) STDDEV = 1.6
      IF(D.GE.451.6.AND.D.LT.461.0) STDDEV = 1.7
      IF(D.GE.461.0.AND.D.LT.468.9) STDDEV = 1.8
      IF(D.GE.468.9.AND.D.LT.475.4) STDDEV = 1.9
      IF(D.GE.475.4.AND.D.LT.480.8) STDDEV = 2.0
      IF(D.GE.480.8.AND.D.LT.485.2) STDDEV = 2.1
      IF(D.GE.485.2.AND.D.LT.488.4) STDDEV = 2.2
      IF(D.GE.488.4.AND.D.LT.491.6) STDDEV = 2.3
      IF(D.GE.491.6.AND.D.LT.494.0) STDDEV = 2.4
      IF(D.GE.494.0.AND.D.LT.495.8) STDDEV = 2.5
      IF(D.GE.495.8.AND.D.LT.497.2) STDDEV = 2.6
      IF(D.GE.497.2.AND.D.LT.498.2) STDDEV = 2.7
      IF(D.GE.498.2.AND.D.LT.499.0) STDDEV = 2.8
      IF(D.GE.499.0.AND.D.LT.499.6) STDDEV = 2.9
      IF(D.GE.499.6.AND.D.LE.500.0) STDDEV = 3.0
C
100   CONTINUE
C
      IF(INJOUT(8).EQ.0) GO TO 200
      IF(D.LT.2.5) STDDEV=0
      IF(D.GE.2.5.AND.D.LT.7.5) STDDEV = 0.0717
      IF(D.GE.7.5.AND.D.LT.17.5) STDDEV = 0.115
      IF(D.GE.17.5.AND.D.LT.37.5) STDDEV = 0.216
      IF(D.GE.37.5.AND.D.LT.75.0) STDDEV = 0.352
      IF(D.GE.75.0.AND.D.LT.125.0) STDDEV = 0.584
      IF(D.GE.125.0.AND.D.LT.375.0) STDDEV = 1.213
      IF(D.GE.375.0.AND.D.LT.625.0) STDDEV = 2.366
      IF(D.GE.625.0.AND.D.LT.825.0) STDDEV = 4.108
      IF(D.GE.825.0.AND.D.LT.925.0) STDDEV = 6.251
      IF(D.GE.925.0.AND.D.LT.962.5) STDDEV = 7.815
      IF(D.GE.962.5.AND.D.LT.982.5) STDDEV = 9.348
      IF(D.GE.982.5.AND.D.LT.992.5) STDDEV = 11.345
      IF(D.GE.992.5.AND.D.LT.997.5) STDDEV = 12.838
      IF(D.GE.997.5.AND.D.LE.1000.0) STDDEV = 16.266
      N = 1
      STDDEV = (STDDEV-3.0)/SQRT(6.0)
C
200   CONTINUE
C
      RETURN
      END
C
C ------------------------------------------
      SUBROUTINE IN55(IA,IX)
C
C         PROGRAM TO INITIALIZE IA
C
      INTEGER IA(1),IX,I,J,K,II
      IA(55) = IX
      J = IX
      K = 1
      DO 1 I = 1,54
       II = MOD(21*I,55)
       IA(II) = K
       K = J - K
       IF (K.LT.0) K = K + 1000000000
       J = IA(II)
  1   CONTINUE
C
      I = IRN55(IA)
      I = IRN55(IA)
      I = IRN55(IA)
      RETURN
       END
C ---------------------------------------------------------------
      FUNCTION IRN55(IA)
C
C           FUNCTION SUBPROGRAM TO GENERATE RANDOM NUMBERS
C
      INTEGER IA(1),I,J
      DO 1 I = 1,24
         J = IA(I) - IA(I + 31)
         IF(J.LT.0) J = J + 1000000000
         IA(I) = J
  1   CONTINUE
C
      DO 2 I = 25,55
         J = IA(I) - IA(I - 24)
         IF(J.LT.0) J = J + 1000000000
```

```
        IA(I) = J
  2   CONTINUE
      IRN55 = 1
      RETURN
      END
C ------------------------------------------------------------------
      SUBROUTINE RAND1(DRT)
C
C    THIS SUBROUTINE GENERATES RANDOM NUMBERS BETWEEN 0 AND 1000.
C
C                 R. Rouse and T. Bugnitz
C                 Programming the IBM Personal Computer: Fortran 77
C                 Holt, Rhinehart, and Winston , 1983
C
      INTEGER IA(55),START1,START2
      REAL X(500)
C
C      DRT IS RANDOM NUMBER BETWEEN 0 AND 1000
C
      CALL GETTIM (I1,I2,I3,I4)
      START1 = ( I1 + I2 + I3 + I4 ) * 1000
      CALL IN55(IA,START1)
      JRAND = JRAND + 1
      IF (JRAND.GT.55) JRAND = IRN55(IA)
      DRT = FLOAT (IA(JRAND)) * 1.0E-9 * 1000
C
      RETURN
      END
C
C  ----------------------------------------------
      SUBROUTINE ICSTTS
C
C       "ICSTTS" stands for:
C       "Incineration Cylindrical 3-d model,
C            Subroutine for Turbulence Time Scale"
C
      LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
      COMMON/DIMCB/
     1       IX, IY, IZ, IXPLUS, IYPLUS, IZPLUS
C
      COMMON/PRTCB/
     1         CASE   , INCASE(80)     , INJOUT(10), INPTYP(10)
     2         , NPRT1 , NPRT2 , NPRT3
C
      COMMON/INPUT/
     1       V(25,15,5), TEMP(25,15,5)
     2       , SUMASS, TIMAX, TEMAX, TEMIN, TAUC, NPART
     3       , II, JI, KI, NCMPND, COMPND, JRAND
     4       , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/BDYCB/
     1       XL(25), XBDY(26), UBDY(26,15,5), UBDY1(26,15,5)
     2       , R(15), YBDY(16), VBDY(25,16,5), VBDY1(25,16,5)
     3       , DTHETA(5), ZBDY(6), WBDY(25,15,6), WBDY1(25,15,6)
     4        , ROTBDY(25,15,6), TWALL(25,15,5), CYL
C
      CALL RANDOM (STDX,NX)
      CALL RANDOM (STDY,NY)
      CALL RANDOM (STDZ,NZ)
C
        DO 100 I = 1,IX
        DO 200 J = 1,IY
        DO 300 K = 1,IZ
        VMAG= SQRT(UBDY1(I,J,K)**2 + VBDY1(I,J,K)**2 + WBDY1(I,J,K)**2)
C
C       OPTION FOR HIGH TURBULENCE
C
        SIGMAX = XSIGMA
        SIGMAY = YSIGMA
        SIGMAZ = ZSIGMA
C
        IF(INJOUT(7).EQ.1) GO TO 400
        IF( VMAG.LE.7.62)  SIGMAX = 1.524
        IF( VMAG.LE.7.62)  SIGMAY = 3.048
        IF( VMAG.LE.7.62)  SIGMAZ = 1.524
        IF(VMAG.GT.15.24) SIGMAX = 0.6096
        IF(VMAG.GT.15.24) SIGMAY = 0.9144
        IF(VMAG.GT.15.24) SIGMAZ = 0.6096
        IF(VMAG.GT.7.62.AND.VMAG.LE.15.24) SIGMAX = 1.22
        IF(VMAG.GT.7.62.AND.VMAG.LE.15.24) SIGMAY = 1.83
        IF(VMAG.GT.7.62.AND.VMAG.LE.15.24) SIGMAZ = 1.22
400     CONTINUE
C
        IF(INJOUT(6).EQ.1) GO TO 420
        IF(INJOUT(6).EQ.2) GO TO 420
        CALL RANDOM(STDX,NX)
        CALL RANDOM (STDY,NY)
        CALL RANDOM (STDZ,NZ)
420     CONTINUE
C
        IF(INJOUT(10).NE.0) STDX = 2.0
        IF(INJOUT(10).NE.0) STDY = 0.0
        IF(INJOUT(10).NE.0) STDZ = 0.0
        IF(INJOUT(10).EQ.1) NX = 1
        IF(INJOUT(10).EQ.2) NX = -1
C
        UBDY(I,J,K) = UBDY1(I,J,K) + STDX * SIGMAX * NX
        VBDY(I,J,K) = VBDY1(I,J,K) + STDY * SIGMAY * NY
        WBDY(I,J,K) = WBDY1(I,J,K) + STDZ * SIGMAZ * NZ
C
 300  CONTINUE
 200  CONTINUE
 100  CONTINUE
C
      RETURN
      END
C -----------------------------------------------------------------
```

```
         (filename:  DROP3D2.FOR)
      SUBROUTINE   ICSSET
C
C     Modified from SETINJ by Mark Sheldon for EER, 4/30/85
C             -
C     PURPOSE:    'ICSSET' Stands for:
C         'Incineration, Cylindrical 3-d model,
C           Subroutine for SETup'
C
          REAL        LHELIQ, LHELIQ1, LHELIQ2
            INTEGER     TIMAX
            LOGICAL*1   COMPND(40,20),CASE(60), INCASE
            LOGICAL     CYL
C
      COMMON/DIMCB/
     1       IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/LIQCB/
     1         TLIQ, TINIT, IDUM
     2       , TBOIL, TBL1, TBL2, TBL3
     3       , DRT2, DRT3, DRT4, DRT3I
     4       , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5       , LHELIQ, LHELIQ1, LHELIQ2
     6       , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7       , HCOMLQ, HCOMLQ1, HCOMLQ2
     8       , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1         ZSAFE , DSAFE , TSAFE , ESAFE , TOL1
     2        ,NDROP , MAXSTP, NRAMP
C
      COMMON/PRTCB/
     1         CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/INPUT/
     1               V(25,15,5),   TEMP(25,15,5)
     2        ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3        ,II    , JI    , KI    , NCMPND, COMPND, JRAND
     4      , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/BDYCB/
     1         XL(25)    , XBDY(26)  , UBDY(26,15,5), UBDY1(26,15,5)
     2        ,R(15)     , YBDY(16)  , VBDY(25,16,5), VBDY1(25,16,5)
     3        ,DTHETA(5) , ZBDY(6)   , WBDY(25,15,6), WBDY1(25,15,6)
     4        ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
      COMMON/SWRLCB/
     1         CFORCE(25,15,6), CFREE(25,15,6)
     2        ,BLAYER, RFORCE, SWIRL , TOTLEN, JLAYER, JFORCE
C
      COMMON/NOZCB/
     1       XNOZ,YNOZ,ZNOZ
     2       ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
```

```
C     DENSITY (KG M**-3), IDEAL GAS AT 1 ATM.
C         (SUMASS IS GMOLES OF GAS PER KG OF GAS)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
C     INITIALIZE CONSTANT PARAMETERS
C
      PI = 3.14159
C
C     INPUT FROM DATA FILE
C
      READ(5,210)(INCASE(I),I=1,70)
210   FORMAT(70A1)
C
      READ(5,220)TINIT
220   FORMAT(8X,F10.4)
C
      READ(5,225)TBL1,TBL2,TBL3
225   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,226)DRT2,DRT3,DRT4
226   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,230)CPLIQ1,CPLIQ2,CPLIQ3
230   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,235)LHELIQ1,LHELIQ2
235   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(5,237)RHOLIQ1,RHOLIQ2,RHOLIQ3
237   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,240)HCOMLQ1,HCOMLQ2
240   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(5,245)AFMRAT1,AFMRAT2,AFMRAT3
245   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,250)XNOZ,YNOZ,ZNOZ
250   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,270)ZSAFE,DSAFE
270   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,280)TSAFE,ESAFE
280   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,290)TOL1,NRAMP
290   FORMAT(8X,F10.4,9X,I10)
C
      READ(5,300)MAXSTP,NDROP
300   FORMAT(8X,I10,9X,I10)
C
      READ(5,310)NPRT1,NPRT2
      READ(5,310)NPRT3
```

```
310   FORMAT(8X,I10,9X,I10)
C
      READ(5,320)INJOUT(1),INJOUT(2)
      READ(5,320)INJOUT(3),INJOUT(4)
      READ(5,320)INJOUT(5),INJOUT(6)
      READ(5,320)INJOUT(7),INJOUT(8)
      READ(5,320)INJOUT(9),INJOUT(10)
C
      READ(5,320)INPTYP(1),INPTYP(2)
      READ(5,320)INPTYP(3),INPTYP(4)
      READ(5,320)INPTYP(5),INPTYP(6)
      READ(5,320)INPTYP(7),INPTYP(8)
320   FORMAT(8X,I10,9X,I10)
C
      READ(5,330) TWDUM,TGDUM
      READ(5,330) UDUM,VDUM
      READ(5,330) SWIRL,TOTLEN
330   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,340) JLAYER, JFORCE
340   FORMAT(8X,I10,9X,I10)
C
      READ(5,341) TIMAX
341   FORMAT(8X,I10)
C
      READ(5,350) TBTS
350   FORMAT(8X,E10.3)
C
      READ(5,355) TRNO
355   FORMAT(8X,F10.6)
C
      READ(5,360) XSIGMA,YSIGMA,ZSIGMA
360   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      DRT3I = DRT4
C
C     WRITE MODEL RUN CONDITIONS TO SCREEN AND RESULT FILES
C
      WRITE(6,400) DRT2,DRT3,DRT4
      WRITE(7,400) DRT2,DRT3,DRT4
      WRITE(8,400) DRT2,DRT3,DRT4
400   FORMAT(2X,'DRT2 = ',F10.4,2X,'DRT3 = ',F10.4,2X,'DRT4 = ',F10.4)
      IF(INPTYP(6).EQ.0) WRITE(6,410) TIMAX
      IF(INPTYP(6).EQ.0) WRITE(7,410) TIMAX
      IF(INPTYP(6).EQ.0) WRITE(8,410) TIMAX
410   FORMAT(2X,'TURBULENCE: NO. OF RUNS = ',I10)
      IF(INPTYP(6).EQ.1) WRITE(6,420)
      IF(INPTYP(6).EQ.1) WRITE(7,420)
      IF(INPTYP(6).EQ.1) WRITE(8,420)
420   FORMAT(2X,'NO TURBULENCE')
      IF(INPTYP(6).EQ.1) GO TO 500
      IF(INJOUT(7).EQ.0) WRITE(6,430)
      IF(INJOUT(7).EQ.0) WRITE(7,430)
      IF(INJOUT(7).EQ.0) WRITE(8,430)
430   FORMAT(2X,'INPUT MEASURED VELOCITY STANDARD DEVIATIONS')
```

```
      IF(INJOUT(7).EQ.1) WRITE(6,440) XSIGMA,YSIGMA,ZSIGMA
      IF(INJOUT(7).EQ.1) WRITE(7,440) XSIGMA,YSIGMA,ZSIGMA
      IF(INJOUT(7).EQ.1) WRITE(8,440) XSIGMA,YSIGMA,ZSIGMA
440   FORMAT(2X,'STANDARD DEVIATIONS: VX = ',F10.4,2X,'VY = '
     1       ,F10.4,2X,'VZ = ',F10.4)
      IF(INJOUT(8).EQ.0) WRITE(6,450)
      IF(INJOUT(8).EQ.0) WRITE(7,450)
      IF(INJOUT(8).EQ.0) WRITE(8,450)
450   FORMAT(2X,'VELOCITIES = NORMAL DISTRIBUTION')
      IF(INJOUT(8).EQ.1) WRITE(6,460)
      IF(INJOUT(8).EQ.1) WRITE(7,460)
      IF(INJOUT(8).EQ.1) WRITE(8,460)
460   FORMAT(2X,'VELOCITIES = CHI-SQUARED DISTRIBUTION')
      IF(INJOUT(10).EQ.1) WRITE(6,465)
      IF(INJOUT(10).EQ.1) WRITE(7,465)
      IF(INJOUT(10).EQ.1) WRITE(8,465)
465   FORMAT(2X,'AXIAL VELOCITY STANDARD DEVIATION = 2 USED')
      IF(INJOUT(10).EQ.2) WRITE(6,467)
      IF(INJOUT(10).EQ.2) WRITE(7,467)
      IF(INJOUT(10).EQ.2) WRITE(8,467)
467   FORMAT(2X,'AXIAL VELOCITY STANDARD DEVIATION = -2 USED')
      IF(INJOUT(6).EQ.0) WRITE(6,470)
      IF(INJOUT(6).EQ.0) WRITE(7,470)
      IF(INJOUT(6).EQ.0) WRITE(8,470)
470   FORMAT(2X,'"RANDOM" CALLED EVERY ZONE')
      IF(INJOUT(6).EQ.1) WRITE(6,480)
      IF(INJOUT(6).EQ.1) WRITE(7,480)
      IF(INJOUT(6).EQ.1) WRITE(8,480)
480   FORMAT(2X,'"RANDOM" CALLED ONCE')
      IF(INJOUT(6).EQ.2) WRITE(6,490) TBTS
      IF(INJOUT(6).EQ.2) WRITE(7,490) TBTS
      IF(INJOUT(6).EQ.2) WRITE(8,490) TBTS
490   FORMAT(2X,'"RANDOM" CALLED EACH TIMESCALE:  TBTS (SEC) = ',E10.3)
500   CONTINUE
      IF(INJOUT(9).EQ.1) WRITE(6,505)
      IF(INJOUT(9).EQ.1) WRITE(7,505)
      IF(INJOUT(9).EQ.1) WRITE(8,505)
505   FORMAT(2X,'DROPLET FINAL CARBON BURNOUT VARIATION')
      IF(INPTYP(7).EQ.1) WRITE(6,507) TRNO
      IF(INPTYP(7).EQ.1) WRITE(7,507) TRNO
      IF(INPTYP(7).EQ.1) WRITE(8,507) TRNO
507   FORMAT(2X,'PHASE 3 TRANSFER NUMBER = ',F10.6)
      IF(INJOUT(5).EQ.1) WRITE(6,510)
      IF(INJOUT(5).EQ.1) WRITE(7,510)
      IF(INJOUT(5).EQ.1) WRITE(8,510)
510   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  GRAVITY = 0')
      IF(INJOUT(5).EQ.2) WRITE(6,520)
      IF(INJOUT(5).EQ.2) WRITE(7,520)
      IF(INJOUT(5).EQ.2) WRITE(8,520)
520   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  DRAG = 0')
      IF(INJOUT(5).EQ.3) WRITE(6,530)
      IF(INJOUT(5).EQ.3) WRITE(7,530)
      IF(INJOUT(5).EQ.3) WRITE(8,530)
530   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  GRAVITY = 0 AND DRAG = 0')
      IF(INJOUT(5).EQ.4) WRITE(6,540)
      IF(INJOUT(5).EQ.4) WRITE(7,540)
      IF(INJOUT(5).EQ.4) WRITE(8,540)
540   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  CD = CDINF')
      IF(INJOUT(5).EQ.5) WRITE(6,550)
      IF(INJOUT(5).EQ.5) WRITE(7,550)
      IF(INJOUT(5).EQ.5) WRITE(8,550)
550   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  Q = 0')
      IF(INJOUT(5).EQ.6) WRITE(6,560)
      IF(INJOUT(5).EQ.6) WRITE(7,560)
      IF(INJOUT(5).EQ.6) WRITE(8,560)
560   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  ETAS = 1')
      IF(INJOUT(5).EQ.7) WRITE(6,570)
      IF(INJOUT(5).EQ.7) WRITE(7,570)
      IF(INJOUT(5).EQ.7) WRITE(8,570)
570   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  ETAE = 1')
C
      IF(INJOUT(5).EQ.5) HCOMLQ1 = 0.0
      IF(INJOUT(5).EQ.5) HCOMLQ2 = 0.0
C
C     COORDINATES OF ZONE BOUNDARIES
C
      XBDY(1) = 0.
      DO 600 I = 1,IX
          XBDY(I+1) = XBDY(I) + XL(I)
600   CONTINUE
C
      YBDY(1) = 0.
      DO 620 J = 1, IY
          YBDY(J+1) = YBDY(J) + R(J)
620   CONTINUE
C
      ZBDY(1) = 0.
      DO 640 K = 1, IZ
          ZBDY(K+1) = ZBDY(K) + DTHETA(K)
640   CONTINUE
C
C     CHECK TO SEE IF ANGULAR SECTORS ADD UP TO 360 DEGREES
C
      CYL = .TRUE.
      DUM1 = 360. - ABS(ZBDY(IZPLUS) - ZBDY(1))
      IF(DUM1.GT.+1.E-8) CYL = .FALSE.
      IF(DUM1.LT.-1.E-8) WRITE(8,650) DUM1
650   FORMAT(1X,'***ICSSET WARNING: SUM OF ANGULAR SECTORS IS'
     1           ,F5.1,' DEGREES OVER 360')
C
C     FIND LIMITS OF FORCED/FREE VORTEX AND BOUNDARY LAYER
C
      IF(JFORCE.GE.1) GOTO 670
          WRITE(8,680) JFORCE
680       FORMAT(1X,'ICSSET CORRECTION: JFORCE VALUE OF ',I3
     1               ,' WOULD CAUSE CENTERLINE ERROR.'
     2           ,/,4X,'CORRECTION: SET JFORCE = 1')
          JFORCE = 1
670   CONTINUE
      RFORCE = YBDY(JFORCE + 1)
      BLAYER = YBDY(IYPLUS) - YBDY(IYPLUS-JLAYER)
C
C     AREAS AND VELOCITIES AT ZONE BOUNDARIES (FROM MASS FLOWS)
C
C     CHECK FOR FLOW ACROSS CENTERLINE
C
      L = 0
      DO 770 K=1,IZ
      DO 770 I=1,IX
         IF(VBDY1(I,1,K).GT.1.E-6)L=1
770   CONTINUE
      IF(L.EQ.1) WRITE(8,780)
780   FORMAT(1X,'***ICSSET WARNING: FLOW ACROSS CENTERLINE NONZERO')
C
C     CONSTANTS FOR TANGENTIAL AND ROTATIONAL GAS VELOCITY
C
C
C     WALL TEMPERATURES
C
      IF(INPTYP(1).EQ.1)GOTO 910
         DO 920 J=1,IY
         DO 920 I=1,IX
           TWALL(I,J,K) = TEMP(I,J,K)
920      CONTINUE
910   CONTINUE
C
C    DUMMY INPUT OPTIONS
C
      IF(INPTYP(1).EQ.0)GOTO 1100
         DO 1110 K=1,IZ
         DO 1110 J=1,IY
         DO 1110 I=1,IX
           TWALL(I,J,K) = TWDUM
1110     CONTINUE
1100  CONTINUE
C
      IF(INPTYP(2).EQ.0)GOTO 1150
         DO 1160 K=1,IZ
         DO 1160 J=1,IY
         DO 1160 I=1,IX
           TEMP(I,J,K) = TGDUM
1160     CONTINUE
1150  CONTINUE
C
      IF(INPTYP(3).EQ.0)GOTO 1200
         DO 1210 K=1,IZ
         DO 1210 J=1,IY
         DO 1210 I=1,IXPLUS
           UBDY1(I,J,K) = UDUM
1210     CONTINUE
1200  CONTINUE
C
      IF(INPTYP(4).EQ.0)GOTO 1250
         DO 1260 K=1,IZ
         DO 1260 J=1,IYPLUS
```

```
            DO 1260 I=1,IX
              VBDY1(I,J,K) = VDUM
1260        CONTINUE
1250    CONTINUE
C
C       DUMMY SWIRL CALCULATION:
C
        IF(INPTYP(5).EQ.0)GOTO 1300
            DO 1320 K=1,IZPLUS
            DO 1320 J=1,IY
            DO 1320 I=1,IX
              DUM2 = ( XBDY(I) + XBDY(I+1) ) * 0.5
              DUM1 = (TOTLEN - DUM2) / (TOTLEN - XBDY(1))
              CFREE(I,J,K) = 4. * SWIRL * UBDY1(1,1,1) * DUM1 * RFORCE
              CFORCE(I,J,K)= 4. * SWIRL * UBDY1(1,1,1) * DUM1 / RFORCE
1320         CONTINUE
1300    CONTINUE
C
C        CALCULATION OF TANGENTIAL AND ROTATIONAL GAS VELOCITIES
C
        IF(INPTYP(5).EQ.1) GO TO 1401
            I1 = IY - JLAYER
            DO 1400 K=1,IZPLUS
            DO 1400 J=1,IY
            DO 1400 I=1,IX
              DUM1 = (YBDY(J+1) + YBDY(J)) * 0.5
              DUM2 = 1.
              IF(J.GT.I1) DUM2 = ( R(IY) - DUM1 ) / BLAYER
              IF(J.LE.JFORCE) GOTO 1410
              CFREE(I,J,K) = WBDY1(I,J,K) * DUM1 / DUM2
                ROTBDY(I,J,K) = WBDY1(I,J,K) / DUM1
1410          CONTINUE
              IF(J.GT.JFORCE) GOTO 1450
              CFORCE(I,J,K) = WBDY1(I,J,K) / DUM1 / DUM2
                ROTBDY(I,J,K) = WBDY1(I,J,K)   / DUM1
1450           CONTINUE
1400         CONTINUE
1401         CONTINUE
C
C       OPTIONAL OUTPUT
C
        IF(INJOUT(2).EQ.1) CALL ICPSET
C
        RETURN
        END
C ------------------------------------------------------------------
```

```
        (filename:  DROP3D3.FOR)
      SUBROUTINE ICSGAS
C
C     Modified from GPROP by Mark Sheldon for EER, 5/1/85
C
C     PURPOSE:
C        "ICSGAS" stands for:
C        "Incineration Cylindrical 3-d model,
C          GAS properties"
C
C     AVAILABLE CHEMICAL SPECIES:
C     No.  Formula  Name
C        1  O2          Diatomic Oxygen
C        2  N2          Diatomic Nitrogen
C        3  CO2         Carbon Dioxide
C        4  H2O         Water Vapor
C
C     Primary Reference:
C          Reid, Prausnitz and Sherwood  (1977)
C          The Properties of Gases and Liquids, 3rd ed.
C
C     LOCAL VARIABLES
C
      REAL*4 CP(4)      , VISC(4)   , COND(4)
     1       ,MASSFR(4) , MOLEFR(4), MOLWT(4)
     2       ,SIGMA(4)  , EPS(4)    , DELTA(4)
     3       ,TCRIT(4)  , KALPH(4)  , KCIR(4)
     4       ,VAFUN(4,4), VWGT(4)   , KWGT(4)
     5       ,VFUDGE(4) , CFUDGE(4), KFUDGE(4)
     6       ,DUM1      , DUM2         , DUM3       , DUM4     , DUM5
     7       ,DUM6      , DUM7         , DUM8       , DUM9
     8       ,TDUM1     , TDUM2
      INTEGER  IPOLAR(4), TIMAX
      LOGICAL WARN1,WARN2
      LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
      COMMON/DIMCB/
     1        IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/PRTCB/
     1        CASE  , INCASE(80)     , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/INPUT/
     1             V(25,15,5),    TEMP(25,15,5)
     2        ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3        ,II    , JI    , KI    , NCMPND, COMPND
     4     , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/GASCB/
     1        CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
     2        ,FO2   , FN2   , FCO2  , FH2O
C
C     MOLECULAR PARAMETERS
C
```

```
C     NUMBER OF GAS SPECIES
      NGSPEC = 4
C
C     MOLECULAR WEIGHTS (G/GMOLE)
      DATA MOLWT /32.00    , 28.02    , 44.01    , 18.02     /
C
C     LENNARD-JONES (AND STOCKMEYER) PARAMETERS
C        (SIGMA IN ANGSTROMS, EPS IN KELVIN)
      DATA SIGMA /3.433    , 3.681    , 3.996    , 2.52      /
      DATA EPS       /113.      , 91.5     , 190.     , 775. /
      DATA DELTA /0.0         , 0.0      , 0.0      , 1.0  /
C
C     CRITICAL TEMPERATURES (KELVIN)
      DATA TCRIT /154.8    , 126.2    , 304.2    , 647.3     /
C
C     PARAMETERS FOR POLAR VERSION OF THERMAL CONDUCTIVITY
C        (IPOLAR IS FLAG: =0 IF NONPOLAR, =1 IF POLAR)
C        (ALPHA AND CIR HAVE UNITS OF CAL/GMOLE/KELVIN)
      DATA IPOLAR/  0,          0,          0,          1/
      DATA KALPH / 0.0         , 0.0      , 0.0      , 0.90 /
      DATA KCIR  / 0.0         , 0.0      , 0.0      , 0.0  /
C
C     FUDGE FACTORS ARE RATIOS OF EXPERIMENTAL TO CALCULATED VALUES
C        AT REFERENCE TEMPERATURE (1300 K UNLESS OTHERWISE NOTED)
C
CNOTE: BEGIN BY USING FUDGE FACTORS SET TO 1.0
C
      DATA VFUDGE/ 1.0         , 1.0      , 1.0      , 1.0  /
      DATA KFUDGE/ 1.0         , 1.0      , 1.0      , 1.0  /
      DATA CFUDGE/ 1.0         , 1.0      , 1.0      , 1.0  /
C
C     INITIALIZE DEBUG OUTPUT LOGIC
C
      WARN1 = .FALSE.
      WARN2 = .FALSE.
C
C     TEMPERATURE-INDEPENDENT CALCULATIONS
C
C     MASS FRACTIONS
C
      MASSFR(1) = FO2
      MASSFR(2) = FN2
      MASSFR(3) = FCO2
      MASSFR(4) = FH2O
C
C     CHECK MASSFR NORMALIZATION
C
      DUM1 = -1.
      DO 210 L = 1,NGSPEC
         DUM1 = MASSFR(L) + DUM1
210    CONTINUE
      IF(DUM1.LT.-1.E-6) WRITE(8,220) DUM1
220   FORMAT(1X,'***ICSGAS WARNING: SUM OF MASS FRACTIONS IS '
     1          ,E10.3,' BELOW 1')
      IF(DUM1.GT.+1.E-6) WRITE(8,230) DUM1
```

```
230   FORMAT(1X,'***ICSGAS WARNING: SUM OF MASS FRACTIONS IS '
     1          ,E10.3,' ABOVE 1')
C
C     MOLE FRACTIONS
C
      DUM1 = 0.
      DO 310 L = 1, NGSPEC
         DUM1 = DUM1 + MASSFR(L)/MOLWT(L)
310   CONTINUE
      DO 320 L = 1, NGSPEC
         MOLEFR(L) = ( MASSFR(L)/MOLWT(L) ) / DUM1
320   CONTINUE
C
C     TEMPERATURE INDEPENDENT WEIGHTING FUNCTION (A) FOR MIX VISCOSITY
C
      DO 330 M = 1, NGSPEC
      DO 330 L = 1, NGSPEC
         DUM1 = MOLWT(L) / MOLWT(M)
         DUM2 = ( 4./ (1. + 1./DUM1) / (1. + DUM1) )**0.25
         DUM3 = DUM2 * (DUM1**(-0.5))
         DUM4 = DUM1 - (DUM1**(0.45))
         DUM5 = 2. * (1. + DUM1)
         DUM6 = (1. + (DUM1**(0.45)) ) * (DUM2**(-0.5))
         DUM7 = 1. + DUM2
         VAFUN(L,M) = DUM3 * (1. + DUM4/ (DUM5 + DUM6/DUM7) )
330   CONTINUE
C
C     LOOP THROUGH ALL ZONES I,J
C
      DO 1000 K = 1, IZ
      DO 1000 J = 1, IY
      DO 1000 I = 1, IX
C
C     LOOP FOR PURE COMPONENT PROPERTIES
C
      DO 2000 L = 1, NGSPEC
C
C     PURE COMPONENT HEAT CAPACITY
C
      TDUM1 = TEMP(I,J,K)*1.8
C
      IF(WARN1) GOTO 430
C
      IF(TDUM1.LT.540.) WRITE(8,410) TDUM1
410   FORMAT(1X,'***ICSGAS WARNING: GAS TEMP=',F8.1,'FARENHEIT, '
     1        ,/,4X,'TOO LOW  FOR EMPIRICAL CP EQNS. IN ICSGAS')
C
      IF(TDUM1.GT.5000.)WRITE(8,420) TDUM1
420   FORMAT(1X,'***ICSGAS WARNING: GAS TEMP=',F8.1,'FARENHEIT, '
     2        ,/,4X,'TOO HIGH FOR EMPIRICAL CP EQNS. IN ICSGAS')
C
      WARN1 = .TRUE.
430   CONTINUE
C
      IF(L.EQ.1) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 11.515 - 172.*( TDUM1**(-0.5) ) + 1530./TDUM1 )
C
      IF(L.EQ.2) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * (   9.47  - 3.47E3 / TDUM1              + 1.16E6/TDUM1/TDUM1 )
C
      IF(L.EQ.3) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 16.2   - 6.53E3 / TDUM1               + 1.41E6/TDUM1/TDUM1 )
C
      IF(L.EQ.4) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1      * ( 19.86  - 597.*( TDUM1**(-0.5) ) + 7500./TDUM1 )
C
C     PURE COMPONENT VISCOSITY
C         (DUM1 IS THE INTEGRAL 'OMEGA' BASED ON STOCKMEYER POTENTIAL)
C
      TDUM1 = TEMP(I,J,K)/EPS(L)
C
      IF(WARN2) GOTO 460
C
      IF(TDUM1.LT.0.3) WRITE(8,440) TDUM1, L, I, J, K
440   FORMAT(1X,'***ICSGAS WARNING: NONDIMEN TEMP = ',F6.2,/,4X
     1        ,'FOR SPECIES L=',I3,' AT ZONE I=',I3,', J=',I3,', K=',I3
     2        ,/,4X,'TOO LOW FOR ACCURATE VISCOSITY PREDICTION')
C
      IF(TDUM1.GT.100.) WRITE(8,450) TDUM1, L, I, J, K
450   FORMAT(1X,'***ICSGAS WARNING: NONDIMEN TEMP = ',F6.2,/,4X
     1        ,'FOR SPECIES L=',I3,' AT ZONE I=',I3,', J=',I3,', K=',I3
     2        ,/,4X,'TOO HIGH FOR ACCURATE VISCOSITY PREDICTION')
C
      WARN2 = .TRUE.
460   CONTINUE
C
      DUM1  =  1.16145 / (TDUM1**0.14874)
     1         + 0.52487 * EXP(-0.77320*TDUM1)
     2         + 2.16178 * EXP(-2.43787*TDUM1)
     3         + 0.2 * DELTA(L) * DELTA(L) / TDUM1
C
      VISC(L) = (26.69E-7 * SQRT( MOLWT(L)*TEMP(I,J,K) )
     1           / SIGMA(L) / SIGMA(L) / DUM1)
     2           * VFUDGE(L)
C
C     PURE COMPONENT THERMAL CONDUCTIVITY
C         (EQUATION HAS 2 FORMS, FOR NONPOLAR AND POLAR SPECIES)
C
      TDUM2 = TEMP(I,J,K)/TCRIT(L)
C
      IF(IPOLAR(L).EQ.0) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1      * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.70 / TDUM2) + 0.9168 )
     3      * KFUDGE(L)
C
      IF(IPOLAR(L).EQ.1) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1      * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.69 / TDUM2) + 1.077
     3           - (3. * KALPH(L)) - (0.3 * KCIR(L))  )
     4      * KFUDGE(L)
```

```
C
2000  CONTINUE
C
C     LOOP FOR MIXTURE WEIGHTING FUNCTIONS
C
      DO 3000 L = 1, NGSPEC
      VWGT(L) = 0.
      KWGT(L) = 0.
      DO 3000 M = 1, NGSPEC
C
C     VISCOSITY WEIGHTING FUNCTION
C
      DUM2 = 1.0
      IF((DELTA(L).GE.0.1).OR.(DELTA(M).GE.0.1))
     1   DUM2 = ( 1. +
     2                SQRT( (TEMP(I,J,K)/EPS(L)) * (TEMP(I,J,K)/EPS(M)) )
     3                   + DELTA(L) * DELTA(M) * 0.25 )
     4       /SQRT( 1. + TEMP(I,J,K)/EPS(L) + DELTA(L)*DELTA(L)*0.25 )
     5       /SQRT( 1. + TEMP(I,J,K)/EPS(M) + DELTA(M)*DELTA(M)*0.25 )
C
      DUM3 = DUM2 * VAFUN(L,M) * SQRT( VISC(L)/VISC(M) )
C
      VWGT(L) = VWGT(L) + DUM3 * MOLEFR(M)
C
C     THERMAL CONDUCTIVITY WEIGHTING FUNCTION
C
      DUM4 = ( 1. + SQRT( VISC(L)/VISC(M) )
     1               *( MOLWT(M)/MOLWT(L) )**0.25 )**2.
     2       / SQRT( 8. * (1. + MOLWT(L)/MOLWT(M) ) )
C
      KWGT(L) = KWGT(L) + DUM4 * MOLEFR(M)
C
3000  CONTINUE
C
C     MIXTURE PROPERTIES
C
      CPGAS(I,J,K)  = 0.0
      DVISCG(I,J,K) = 0.0
      TCONDG(I,J,K) = 0.0
C
      DO 4000 L = 1, NGSPEC
         CPGAS(I,J,K)  = CPGAS(I,J,K)  + CP(L)  * MASSFR(L)
         DVISCG(I,J,K) = DVISCG(I,J,K) + VISC(L) * MOLEFR(L) / VWGT(L)
         TCONDG(I,J,K) = TCONDG(I,J,K) + COND(L) * MOLEFR(L) / KWGT(L)
4000  CONTINUE
C
1000  CONTINUE
C
C     OPTIONAL OUTPUT
C
      IF(INJOUT(1).EQ.1) CALL ICPGAS
C
      RETURN
      END
C --------------------------------------------------------------------
```

```
        (filename:  DROP3D2.FOR)
      SUBROUTINE   ICSSET
C
C     Modified from SETINJ by Mark Sheldon for EER, 4/30/85
C
C     PURPOSE:      "ICSSET" Stands for:
C        "Incineration, Cylindrical 3-d model,
C          Subroutine for SETup"
C
          REAL        LHELIQ, LHELIQ1, LHELIQ2
            INTEGER     TIMAX
            LOGICAL*1   COMPND(40,20),CASE(60), INCASE
            LOGICAL     CYL
C
      COMMON/DIMCB/
     1          IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4, DRT3I
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1          ZSAFE , DSAFE , TSAFE , ESAFE , TOL1
     2         ,NDROP , MAXSTP, NRAMP
C
      COMMON/PRTCB/
     1          CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2         ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/INPUT/
     1                V(25,15,5),    TEMP(25,15,5)
     2         ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC   , NPART
     3         ,II    , JI    , KI    , NCMPND, COMPND, JRAND
     4       , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/BDYCB/
     1          XL(25)     , XBDY(26)   , UBDY(26,15,5), UBDY1(26,15,5)
     2         ,R(15)      , YBDY(16)   , VBDY(25,16,5), VBDY1(25,16,5)
     3         ,DTHETA(5)  , ZBDY(6)    , WBDY(25,15,6), WBDY1(25,15,6)
     4         ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
      COMMON/SWRLCB/
     1          CFORCE(25,15,6), CFREE(25,15,6)
     2         ,BLAYER, RFORCE, SWIRL , TOTLEN, JLAYER, JFORCE
C
      COMMON/NOZCB/
     1        XNOZ,YNOZ,ZNOZ
     2        ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
```

```
C     DENSITY (KG M**-3), IDEAL GAS AT 1 ATM.
C         (SUMASS IS GMOLES OF GAS PER KG OF GAS)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
C     INITIALIZE CONSTANT PARAMETERS
C
      PI = 3.14159
C
C     INPUT FROM DATA FILE
C
      READ(5,210)(INCASE(I),I=1,70)
210   FORMAT(70A1)
C
      READ(5,220)TINIT
220   FORMAT(8X,F10.4)
C
      READ(5,225)TBL1,TBL2,TBL3
225   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,226)DRT2,DRT3,DRT4
226   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,230)CPLIQ1,CPLIQ2,CPLIQ3
230   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,235)LHELIQ1,LHELIQ2
235   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(5,237)RHOLIQ1,RHOLIQ2,RHOLIQ3
237   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,240)HCOMLQ1,HCOMLQ2
240   FORMAT(8X,E10.3,9X,E10.3)
C
      READ(5,245)AFMRAT1,AFMRAT2,AFMRAT3
245   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,250)XNOZ,YNOZ,ZNOZ
250   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      READ(5,270)ZSAFE,DSAFE
270   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,280)TSAFE,ESAFE
280   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,290)TOL1,NRAMP
290   FORMAT(8X,F10.4,9X,I10)
C
      READ(5,300)MAXSTP,NDROP
300   FORMAT(8X,I10,9X,I10)
C
      READ(5,310)NPRT1,NPRT2
      READ(5,310)NPRT3
```

```
310   FORMAT(8X,I10,9X,I10)
C
      READ(5,320)INJOUT(1),INJOUT(2)
      READ(5,320)INJOUT(3),INJOUT(4)
      READ(5,320)INJOUT(5),INJOUT(6)
      READ(5,320)INJOUT(7),INJOUT(8)
      READ(5,320)INJOUT(9),INJOUT(10)
C
      READ(5,320)INPTYP(1),INPTYP(2)
      READ(5,320)INPTYP(3),INPTYP(4)
      READ(5,320)INPTYP(5),INPTYP(6)
      READ(5,320)INPTYP(7),INPTYP(8)
320   FORMAT(8X,I10,9X,I10)
C
      READ(5,330) TWDUM,TGDUM
      READ(5,330) UDUM,VDUM
      READ(5,330) SWIRL,TOTLEN
330   FORMAT(8X,F10.4,9X,F10.4)
C
      READ(5,340) JLAYER, JFORCE
340   FORMAT(8X,I10,9X,I10)
C
      READ(5,341) TIMAX
341   FORMAT(8X,I10)
C
      READ(5,350) TBTS
350   FORMAT(8X,E10.3)
C
      READ(5,355) TRNO
355   FORMAT(8X,F10.6)
C
      READ(5,360) XSIGMA,YSIGMA,ZSIGMA
360   FORMAT(8X,F10.4,9X,F10.4,9X,F10.4)
C
      DRT3I = DRT4
C
C     WRITE MODEL RUN CONDITIONS TO SCREEN AND RESULT FILES
C
      WRITE(6,400) DRT2,DRT3,DRT4
      WRITE(7,400) DRT2,DRT3,DRT4
      WRITE(8,400) DRT2,DRT3,DRT4
400   FORMAT(2X,'DRT2 = ',F10.4,2X,'DRT3 = ',F10.4,2X,'DRT4 = ',F10.4)
      IF(INPTYP(6).EQ.0) WRITE(6,410) TIMAX
      IF(INPTYP(6).EQ.0) WRITE(7,410) TIMAX
      IF(INPTYP(6).EQ.0) WRITE(8,410) TIMAX
410   FORMAT(2X,'TURBULENCE: NO. OF RUNS = ',I10)
      IF(INPTYP(6).EQ.1) WRITE(6,420)
      IF(INPTYP(6).EQ.1) WRITE(7,420)
      IF(INPTYP(6).EQ.1) WRITE(8,420)
420   FORMAT(2X,'NO TURBULENCE')
      IF(INPTYP(6).EQ.1) GO TO 500
      IF(INJOUT(7).EQ.0) WRITE(6,430)
      IF(INJOUT(7).EQ.0) WRITE(7,430)
      IF(INJOUT(7).EQ.0) WRITE(8,430)
430   FORMAT(2X,'INPUT MEASURED VELOCITY STANDARD DEVIATIONS')
```

```
      IF(INJOUT(7).EQ.1) WRITE(6,440) XSIGMA,YSIGMA,ZSIGMA
      IF(INJOUT(7).EQ.1) WRITE(7,440) XSIGMA,YSIGMA,ZSIGMA
      IF(INJOUT(7).EQ.1) WRITE(8,440) XSIGMA,YSIGMA,ZSIGMA
440   FORMAT(2X,'STANDARD DEVIATIONS: VX = ',F10.4,2X,'VY = '
     1       ,F10.4,2X,'VZ = ',F10.4)
      IF(INJOUT(8).EQ.0) WRITE(6,450)
      IF(INJOUT(8).EQ.0) WRITE(7,450)
      IF(INJOUT(8).EQ.0) WRITE(8,450)
450   FORMAT(2X,'VELOCITIES = NORMAL DISTRIBUTION')
      IF(INJOUT(8).EQ.1) WRITE(6,460)
      IF(INJOUT(8).EQ.1) WRITE(7,460)
      IF(INJOUT(8).EQ.1) WRITE(8,460)
460   FORMAT(2X,'VELOCITIES = CHI-SQUARED DISTRIBUTION')
      IF(INJOUT(10).EQ.1) WRITE(6,465)
      IF(INJOUT(10).EQ.1) WRITE(7,465)
      IF(INJOUT(10).EQ.1) WRITE(8,465)
465   FORMAT(2X,'AXIAL VELOCITY STANDARD DEVIATION = 2 USED')
      IF(INJOUT(10).EQ.2) WRITE(6,467)
      IF(INJOUT(10).EQ.2) WRITE(7,467)
      IF(INJOUT(10).EQ.2) WRITE(8,467)
467   FORMAT(2X,'AXIAL VELOCITY STANDARD DEVIATION = -2 USED')
      IF(INJOUT(6).EQ.0) WRITE(6,470)
      IF(INJOUT(6).EQ.0) WRITE(7,470)
      IF(INJOUT(6).EQ.0) WRITE(8,470)
470   FORMAT(2X,'"RANDOM" CALLED EVERY ZONE')
      IF(INJOUT(6).EQ.1) WRITE(6,480)
      IF(INJOUT(6).EQ.1) WRITE(7,480)
      IF(INJOUT(6).EQ.1) WRITE(8,480)
480   FORMAT(2X,'"RANDOM" CALLED ONCE')
      IF(INJOUT(6).EQ.2) WRITE(6,490) TBTS
      IF(INJOUT(6).EQ.2) WRITE(7,490) TBTS
      IF(INJOUT(6).EQ.2) WRITE(8,490) TBTS
490   FORMAT(2X,'"RANDOM" CALLED EACH TIMESCALE:  TBTS (SEC) = ',E10.3)
500   CONTINUE
      IF(INJOUT(9).EQ.1) WRITE(6,505)
      IF(INJOUT(9).EQ.1) WRITE(7,505)
      IF(INJOUT(9).EQ.1) WRITE(8,505)
505   FORMAT(2X,'DROPLET FINAL CARBON BURNOUT VARIATION')
      IF(INPTYP(7).EQ.1) WRITE(6,507) TRNO
      IF(INPTYP(7).EQ.1) WRITE(7,507) TRNO
      IF(INPTYP(7).EQ.1) WRITE(8,507) TRNO
507   FORMAT(2X,'PHASE 3 TRANSFER NUMBER = ',F10.6)
      IF(INJOUT(5).EQ.1) WRITE(6,510)
      IF(INJOUT(5).EQ.1) WRITE(7,510)
      IF(INJOUT(5).EQ.1) WRITE(8,510)
510   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  GRAVITY = 0')
      IF(INJOUT(5).EQ.2) WRITE(6,520)
      IF(INJOUT(5).EQ.2) WRITE(7,520)
      IF(INJOUT(5).EQ.2) WRITE(8,520)
520   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  DRAG = 0')
      IF(INJOUT(5).EQ.3) WRITE(6,530)
      IF(INJOUT(5).EQ.3) WRITE(7,530)
      IF(INJOUT(5).EQ.3) WRITE(8,530)
530   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  GRAVITY = 0 AND DRAG = 0')
      IF(INJOUT(5).EQ.4) WRITE(6,540)
      IF(INJOUT(5).EQ.4) WRITE(7,540)
      IF(INJOUT(5).EQ.4) WRITE(8,540)
540   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  CD = CDINF')
      IF(INJOUT(5).EQ.5) WRITE(6,550)
      IF(INJOUT(5).EQ.5) WRITE(7,550)
      IF(INJOUT(5).EQ.5) WRITE(8,550)
550   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  Q = 0')
      IF(INJOUT(5).EQ.6) WRITE(6,560)
      IF(INJOUT(5).EQ.6) WRITE(7,560)
      IF(INJOUT(5).EQ.6) WRITE(8,560)
560   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  ETAS = 1')
      IF(INJOUT(5).EQ.7) WRITE(6,570)
      IF(INJOUT(5).EQ.7) WRITE(7,570)
      IF(INJOUT(5).EQ.7) WRITE(8,570)
570   FORMAT(2X,'SPECIAL MODEL CONSTRAINT:  ETAE = 1')
C
      IF(INJOUT(5).EQ.5) HCOMLQ1 = 0.0
      IF(INJOUT(5).EQ.5) HCOMLQ2 = 0.0
C
C     COORDINATES OF ZONE BOUNDARIES
C
      XBDY(1) = 0.
      DO 600 I = 1,IX
         XBDY(I+1) = XBDY(I) + XL(I)
600   CONTINUE
C
      YBDY(1) = 0.
      DO 620 J = 1, IY
         YBDY(J+1) = YBDY(J) + R(J)
620   CONTINUE
C
      ZBDY(1) = 0.
      DO 640 K = 1, IZ
         ZBDY(K+1) = ZBDY(K) + DTHETA(K)
640   CONTINUE
C
C     CHECK TO SEE IF ANGULAR SECTORS ADD UP TO 360 DEGREES
C
      CYL = .TRUE.
      DUM1 = 360. - ABS(ZBDY(IZPLUS) - ZBDY(1))
      IF(DUM1.GT.+1.E-8) CYL = .FALSE.
      IF(DUM1.LT.-1.E-8) WRITE(8,650) DUM1
650   FORMAT(1X,'***ICSSET WARNING: SUM OF ANGULAR SECTORS IS'
     1          ,F5.1,' DEGREES OVER 360')
C
C     FIND LIMITS OF FORCED/FREE VORTEX AND BOUNDARY LAYER
C
      IF(JFORCE.GE.1) GOTO 670
         WRITE(8,680) JFORCE
680      FORMAT(1X,'ICSSET CORRECTION: JFORCE VALUE OF ',I3
     1              ,' WOULD CAUSE CENTERLINE ERROR.'
     2          ,/,4X,'CORRECTION: SET JFORCE = 1')
         JFORCE = 1
670   CONTINUE
      RFORCE = YBDY(JFORCE + 1)
      BLAYER = YBDY(IYPLUS) - YBDY(IYPLUS-JLAYER)
C
C     AREAS AND VELOCITIES AT ZONE BOUNDARIES (FROM MASS FLOWS)
C
C     CHECK FOR FLOW ACROSS CENTERLINE
C
      L = 0
      DO 770 K=1,IZ
      DO 770 I=1,IX
         IF(VBDY1(I,1,K).GT.1.E-6)L=1
770   CONTINUE
      IF(L.EQ.1) WRITE(8,780)
780   FORMAT(1X,'***ICSSET WARNING: FLOW ACROSS CENTERLINE NONZERO')
C
C     CONSTANTS FOR TANGENTIAL AND ROTATIONAL GAS VELOCITY
C
C
C     WALL TEMPERATURES
C
      IF(INPTYP(1).EQ.1)GOTO 910
         DO 920 J=1,IY
         DO 920 I=1,IX
           TWALL(I,J,K) = TEMP(I,J,K)
920      CONTINUE
910   CONTINUE
C
C    DUMMY INPUT OPTIONS
C
      IF(INPTYP(1).EQ.0)GOTO 1100
         DO 1110 K=1,IZ
         DO 1110 J=1,IY
         DO 1110 I=1,IX
           TWALL(I,J,K) = TWDUM
1110     CONTINUE
1100  CONTINUE
C
      IF(INPTYP(2).EQ.0)GOTO 1150
         DO 1160 K=1,IZ
         DO 1160 J=1,IY
         DO 1160 I=1,IX
           TEMP(I,J,K) = TGDUM
1160     CONTINUE
1150  CONTINUE
C
      IF(INPTYP(3).EQ.0)GOTO 1200
         DO 1210 K=1,IZ
         DO 1210 J=1,IY
         DO 1210 I=1,IXPLUS
           UBDY1(I,J,K) = UDUM
1210     CONTINUE
1200  CONTINUE
C
      IF(INPTYP(4).EQ.0)GOTO 1250
         DO 1260 K=1,IZ
         DO 1260 J=1,IYPLUS
```

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          DO 1260 I=1,IX
            VBDY1(I,J,K) = VDUM
1260      CONTINUE
1250  CONTINUE
C
C     DUMMY SWIRL CALCULATION:
C
      IF(INPTYP(5).EQ.0)GOTO 1300
          DO 1320 K=1,IZPLUS
          DO 1320 J=1,IY
          DO 1320 I=1,IX
            DUM2 = ( XBDY(I) + XBDY(I+1) ) * 0.5
            DUM1 = (TOTLEN - DUM2) / (TOTLEN - XBDY(1))
            CFREE(I,J,K) = 4. * SWIRL * UBDY1(1,1,1) * DUM1 * RFORCE
            CFORCE(I,J,K)= 4. * SWIRL * UBDY1(1,1,1) * DUM1 / RFORCE
1320       CONTINUE
1300  CONTINUE
C
C      CALCULATION OF TANGENTIAL AND ROTATIONAL GAS VELOCITIES
C
      IF(INPTYP(5).EQ.1) GO TO 1401
          I1 = IY - JLAYER
          DO 1400 K=1,IZPLUS
          DO 1400 J=1,IY
          DO 1400 I=1,IX
            DUM1 = (YBDY(J+1) + YBDY(J)) * 0.5
            DUM2 = 1.
            IF(J.GT.I1) DUM2 = ( R(IY) - DUM1 ) / BLAYER
            IF(J.LE.JFORCE) GOTO 1410
            CFREE(I,J,K) = WBDY1(I,J,K) * DUM1 / DUM2
              ROTBDY(I,J,K) = WBDY1(I,J,K) / DUM1
1410        CONTINUE
            IF(J.GT.JFORCE) GOTO 1450
            CFORCE(I,J,K) = WBDY1(I,J,K) / DUM1 / DUM2
              ROTBDY(I,J,K) = WBDY1(I,J,K)   / DUM1
1450         CONTINUE
1400       CONTINUE
1401       CONTINUE
C
C     OPTIONAL OUTPUT
C
      IF(INJOUT(2).EQ.1) CALL ICPSET
C
      RETURN
      END
C ------------------------------------------------------------------------
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```
         (filename:  DROP3D3.FOR)
      SUBROUTINE ICSGAS
C
C     Modified from GPROP by Mark Sheldon for EER, 5/1/85
C
C     PURPOSE:
C        "ICSGAS" stands for:
C        "Incineration Cylindrical 3-d model,
C          GAS properties"
C
C     AVAILABLE CHEMICAL SPECIES:
C     No.  Formula  Name
C        1  O2          Diatomic Oxygen
C        2  N2          Diatomic Nitrogen
C        3  CO2         Carbon Dioxide
C        4  H2O         Water Vapor
C
C     Primary Reference:
C           Reid, Prausnitz and Sherwood  (1977)
C           The Properties of Gases and Liquids, 3rd ed.
C
C     LOCAL VARIABLES
C
      REAL*4 CP(4)      , VISC(4)   , COND(4)
     1       ,MASSFR(4) , MOLEFR(4), MOLWT(4)
     2       ,SIGMA(4)  , EPS(4)    , DELTA(4)
     3       ,TCRIT(4)  , KALPH(4)  , KCIR(4)
     4       ,VAFUN(4,4), VWGT(4)   , KWGT(4)
     5       ,VFUDGE(4) , CFUDGE(4), KFUDGE(4)
     6       ,DUM1      , DUM2           , DUM3       , DUM4    , DUM5
     7       ,DUM6      , DUM7           , DUM8       , DUM9
     8       ,TDUM1     , TDUM2
      INTEGER  IPOLAR(4), TIMAX
      LOGICAL WARN1,WARN2
      LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
      COMMON/DIMCB/
     1        IX     , IY     , IZ     , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/PRTCB/
     1        CASE  , INCASE(80)     , INJOUT(10), INPTYP(10)
     2       ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/INPUT/
     1                V(25,15,5),   TEMP(25,15,5)
     2       ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC   , NPART
     3       ,II    , JI    , KI    , NCMPND, COMPND
     4      , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/GASCB/
     1        CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
     2       ,FO2   , FN2   , FCO2  , FH2O
C
C     MOLECULAR PARAMETERS
C
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```
C     NUMBER OF GAS SPECIES
      NGSPEC = 4
C
C     MOLECULAR WEIGHTS (G/GMOLE)
      DATA MOLWT /32.00   , 28.02   , 44.01   , 18.02     /
C
C     LENNARD-JONES (AND STOCKMEYER) PARAMETERS
C         (SIGMA IN ANGSTROMS, EPS IN KELVIN)
      DATA SIGMA /3.433   , 3.681   , 3.996   , 2.52      /
      DATA EPS      /113.     , 91.5    , 190.     , 775. /
      DATA DELTA /0.0         , 0.0     , 0.0      , 1.0  /
C
C     CRITICAL TEMPERATURES (KELVIN)
      DATA TCRIT /154.8   , 126.2   , 304.2   , 647.3     /
C
C     PARAMETERS FOR POLAR VERSION OF THERMAL CONDUCTIVITY
C         (IPOLAR IS FLAG: =0 IF NONPOLAR, =1 IF POLAR)
C         (ALPHA AND CIR HAVE UNITS OF CAL/GMOLE/KELVIN)
      DATA IPOLAR/  0,          0,          0,         1/
      DATA KALPH / 0.0         , 0.0     , 0.0     , 0.90 /
      DATA KCIR  / 0.0         , 0.0     , 0.0     , 0.0  /
C
C     FUDGE FACTORS ARE RATIOS OF EXPERIMENTAL TO CALCULATED VALUES
C         AT REFERENCE TEMPERATURE (1300 K UNLESS OTHERWISE NOTED)
C
CNOTE: BEGIN BY USING FUDGE FACTORS SET TO 1.0
C
      DATA VFUDGE/ 1.0         , 1.0     , 1.0     , 1.0  /
      DATA KFUDGE/ 1.0         , 1.0     , 1.0     , 1.0  /
      DATA CFUDGE/ 1.0         , 1.0     , 1.0     , 1.0  /
C
C     INITIALIZE DEBUG OUTPUT LOGIC
C
      WARN1 = .FALSE.
      WARN2 = .FALSE.
C
C     TEMPERATURE-INDEPENDENT CALCULATIONS
C
C     MASS FRACTIONS
C
      MASSFR(1) = FO2
      MASSFR(2) = FN2
      MASSFR(3) = FCO2
      MASSFR(4) = FH2O
C
C     CHECK MASSFR NORMALIZATION
C
      DUM1 = -1.
      DO 210 L = 1,NGSPEC
         DUM1 = MASSFR(L) + DUM1
210    CONTINUE
      IF(DUM1.LT.-1.E-6) WRITE(8,220) DUM1
220   FORMAT(1X,'***ICSGAS WARNING: SUM OF MASS FRACTIONS IS '
     1          ,E10.3,' BELOW 1')
      IF(DUM1.GT.+1.E-6) WRITE(8,230) DUM1
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230   FORMAT(1X,'***ICSGAS WARNING: SUM OF MASS FRACTIONS IS '
     1           ,E10.3,' ABOVE 1')
C
C     MOLE FRACTIONS
C
      DUM1 = 0.
      DO 310 L = 1, NGSPEC
         DUM1 = DUM1 + MASSFR(L)/MOLWT(L)
310   CONTINUE
      DO 320 L = 1, NGSPEC
         MOLEFR(L) = ( MASSFR(L)/MOLWT(L) ) / DUM1
320   CONTINUE
C
C     TEMPERATURE INDEPENDENT WEIGHTING FUNCTION (A) FOR MIX VISCOSITY
C
      DO 330 M = 1, NGSPEC
      DO 330 L = 1, NGSPEC
         DUM1 = MOLWT(L) / MOLWT(M)
         DUM2 = ( 4./ (1. + 1./DUM1) / (1. + DUM1) )**0.25
         DUM3 = DUM2 * (DUM1**(-0.5))
         DUM4 = DUM1 - (DUM1**(0.45))
         DUM5 = 2. * (1. + DUM1)
         DUM6 = (1. + (DUM1**(0.45)) ) * (DUM2**(-0.5))
         DUM7 = 1. + DUM2
         VAFUN(L,M) = DUM3 * (1. + DUM4/ (DUM5 + DUM6/DUM7) )
330   CONTINUE
C
C     LOOP THROUGH ALL ZONES I,J
C
      DO 1000 K = 1, IZ
      DO 1000 J = 1, IY
      DO 1000 I = 1, IX
C
C     LOOP FOR PURE COMPONENT PROPERTIES
C
      DO 2000 L = 1, NGSPEC
C
C     PURE COMPONENT HEAT CAPACITY
C
      TDUM1 = TEMP(I,J,K)*1.8
C
      IF(WARN1) GOTO 430
C
      IF(TDUM1.LT.540.) WRITE(8,410) TDUM1
410   FORMAT(1X,'***ICSGAS WARNING: GAS TEMP=',F8.1,'FARENHEIT, '
     1       ,/,4X,'TOO LOW  FOR EMPIRICAL CP EQNS. IN ICSGAS')
C
      IF(TDUM1.GT.5000.)WRITE(8,420) TDUM1
420   FORMAT(1X,'***ICSGAS WARNING: GAS TEMP=',F8.1,'FARENHEIT, '
     2       ,/,4X,'TOO HIGH FOR EMPIRICAL CP EQNS. IN ICSGAS')
C
      WARN1 = .TRUE.
430   CONTINUE
C
      IF(L.EQ.1) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1       * ( 11.515 - 172.*( TDUM1**(-0.5) ) + 1530./TDUM1 )
C
      IF(L.EQ.2) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1       * (    9.47  - 3.47E3 / TDUM1                 + 1.16E6/TDUM1/TDUM1 )
C
      IF(L.EQ.3) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1       * ( 16.2   - 6.53E3 / TDUM1                   + 1.41E6/TDUM1/TDUM1 )
C
      IF(L.EQ.4) CP(L) = ( 4186.5 * CFUDGE(L) / MOLWT(L) )
     1       * ( 19.86  - 597.*( TDUM1**(-0.5) ) + 7500./TDUM1 )
C
C     PURE COMPONENT VISCOSITY
C         (DUM1 IS THE INTEGRAL 'OMEGA' BASED ON STOCKMEYER POTENTIAL)
C
      TDUM1 = TEMP(I,J,K)/EPS(L)
C
      IF(WARN2) GOTO 460
C
      IF(TDUM1.LT.0.3) WRITE(8,440) TDUM1, L, I, J, K
440   FORMAT(1X,'***ICSGAS WARNING: NONDIMEN TEMP = ',F6.2,/,4X
     1         ,'FOR SPECIES L=',I3,' AT ZONE I=',I3,', J=',I3,', K=',I3
     2         ,/,4X,'TOO LOW FOR ACCURATE VISCOSITY PREDICTION')
C
      IF(TDUM1.GT.100.) WRITE(8,450) TDUM1, L, I, J, K
450   FORMAT(1X,'***ICSGAS WARNING: NONDIMEN TEMP = ',F6.2,/,4X
     1         ,'FOR SPECIES L=',I3,' AT ZONE I=',I3,', J=',I3,', K=',I3
     2         ,/,4X,'TOO HIGH FOR ACCURATE VISCOSITY PREDICTION')
C
      WARN2 = .TRUE.
460   CONTINUE
C
      DUM1  =  1.16145 / (TDUM1**0.14874)
     1          + 0.52487 * EXP(-0.77320*TDUM1)
     2          + 2.16178 * EXP(-2.43787*TDUM1)
     3          + 0.2 * DELTA(L) * DELTA(L) / TDUM1
C
      VISC(L) = (26.69E-7 * SQRT( MOLWT(L)*TEMP(I,J,K) )
     1           / SIGMA(L) / SIGMA(L) / DUM1)
     2           * VFUDGE(L)
C
C     PURE COMPONENT THERMAL CONDUCTIVITY
C         (EQUATION HAS 2 FORMS, FOR NONPOLAR AND POLAR SPECIES)
C
      TDUM2 = TEMP(I,J,K)/TCRIT(L)
C
      IF(IPOLAR(L).EQ.0) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1       * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.70 / TDUM2) + 0.9168 )
     3       * KFUDGE(L)
C
      IF(IPOLAR(L).EQ.1) COND(L) = (4.184E3 * VISC(L) / MOLWT(L))
     1       * (    3.107E-4 * CP(L) * MOLWT(L)
     2           - (0.69 / TDUM2) + 1.077
     3           - (3. * KALPH(L)) - (0.3 * KCIR(L))  )
     4       * KFUDGE(L)
```

```
C
2000  CONTINUE
C
C     LOOP FOR MIXTURE WEIGHTING FUNCTIONS
C
      DO 3000 L = 1, NGSPEC
      VWGT(L) = 0.
      KWGT(L) = 0.
      DO 3000 M = 1, NGSPEC
C
C     VISCOSITY WEIGHTING FUNCTION
C
      DUM2 = 1.0
      IF((DELTA(L).GE.0.1).OR.(DELTA(M).GE.0.1))
     1    DUM2 = ( 1. +
     2             SQRT( (TEMP(I,J,K)/EPS(L)) * (TEMP(I,J,K)/EPS(M)) )
     3                + DELTA(L) * DELTA(M) * 0.25 )
     4        /SQRT( 1. + TEMP(I,J,K)/EPS(L) + DELTA(L)*DELTA(L)*0.25 )
     5        /SQRT( 1. + TEMP(I,J,K)/EPS(M) + DELTA(M)*DELTA(M)*0.25 )
C
      DUM3 = DUM2 * VAFUN(L,M) * SQRT( VISC(L)/VISC(M) )
C
      VWGT(L) = VWGT(L) + DUM3 * MOLEFR(M)
C
C     THERMAL CONDUCTIVITY WEIGHTING FUNCTION
C
      DUM4 = ( 1. + SQRT( VISC(L)/VISC(M) )
     1              *( MOLWT(M)/MOLWT(L) )**0.25 )**2.
     2        / SQRT( 8. * (1. + MOLWT(L)/MOLWT(M) ) )
C
      KWGT(L) = KWGT(L) + DUM4 * MOLEFR(M)
C
3000  CONTINUE
C
C     MIXTURE PROPERTIES
C
      CPGAS(I,J,K)  = 0.0
      DVISCG(I,J,K) = 0.0
      TCONDG(I,J,K) = 0.0
C
      DO 4000 L = 1, NGSPEC
         CPGAS(I,J,K)  = CPGAS(I,J,K)  + CP(L) * MASSFR(L)
         DVISCG(I,J,K) = DVISCG(I,J,K) + VISC(L) * MOLEFR(L) / VWGT(L)
         TCONDG(I,J,K) = TCONDG(I,J,K) + COND(L) * MOLEFR(L) / KWGT(L)
4000  CONTINUE
C
1000  CONTINUE
C
C     OPTIONAL OUTPUT
C
      IF(INJOUT(1).EQ.1) CALL ICPGAS
C
      RETURN
      END
C -----------------------------------------------------------------
```

```
C
550   CONTINUE
C
      IF(DIAM.GE.DINIT2) GO TO 800
        IF(IDUM.EQ.0) WRITE(7,810) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
        IF(IDUM.EQ.0) WRITE(8,810) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
810     FORMAT(/ ' DROP ENTERS PHASE 2 AT T (SEC) = ',E10.3,
     1         ' AND D (M) = ',E10.3/ ' X (M) = ',F7.4,' Y (M) = ',
     2        F7.4,' Z (DEG) = ',F7.1,' T (K) = ',F7.1/)
        IF(IDUM.EQ.0) IDUM = 1
        TBOIL = TBL2
        CPLIQ = CPLIQ2
        LHELIQ = LHELIQ2
        RHOLIQ = RHOLIQ2
        HCOMLQ = HCOMLQ2
        AFMRAT = AFMRAT2
        IF(DIAM.GE.DINIT3) GO TO 800
          IF(IDUM.EQ.1) WRITE(7,820) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
          IF(IDUM.EQ.1) WRITE(8,820) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
820       FORMAT(/ ' DROP ENTERS PHASE 3 AT T (SEC) ='',E10.3,
     1           ' AND D (M) = ',E10.3/ ' X (M) = ',F7.4,' Y (M) = ',
     2           F7.4,' Z (DEG) = ',F7.1,' T (K) = ',F7.1/)
          IDUM = 2
          TBOIL = TBL3
          CPLIQ = CPLIQ3
          RHOLIQ = RHOLIQ3
          AFMRAT = AFMRAT3
          IF(DIAM.GE.DINIT4) GO TO 800
            GETOUT = .TRUE.
            XPOLD = XPNEW
            YPOLD = YPNEW
            UPOLD = UPNEW
            VPOLD = VPNEW
            TIME = TIME + DTIME
            WRITE(7,830) DINIT4,DIAM
            WRITE(8,830) DINIT4,DIAM
830         FORMAT(' DROPLET CONSIDERED GONE WHEN DIAMETER IS'
     1             , ' LESS THAN ',E10.3,' M'/ ' D (M) = ',E10.3)
            DIAM = 0.0
            RETURN
800   CONTINUE
      IF(TLNEW.LT.TBOIL) BOIL = .FALSE.
C
      DUM1 = ABS(UGAS-UPNEW)
      DUM2 = ABS(VGAS-VPNEW)
      DUM3 = ABS(WGAS-WPNEW)
      IF((DUM1.GT.TOL1).OR.(DUM2.GT.TOL1).OR.(DUM3.GT.TOL1)) GOTO 580
          IF(.NOT.CNVRG) WRITE(8,590) TOL1
590       FORMAT(1X,'DROPLET AT STREAM VELOCITY TO WITHIN ',E10.3,' M/S')
          CNVRG = .TRUE.
580   CONTINUE
C
C     NEW QUANTITIES BECOME OLD FOR NEXT TIMESTEP
C
      XPOLD = XPNEW
      YPOLD = YPNEW
      ZPOLD = ZPNEW
C
      UPOLD = UPNEW
      VPOLD = VPNEW
      WPOLD = WPNEW
C
      TLIQ  = TLNEW
      TIME  = TIME + DTIME
C
      IF(INJOUT(6).NE.2.OR.INPTYP(6).EQ.1) GO TO 900
        DUMO = TBTS * ITBTS
        IF(TIME.LT.DUMO) GO TO 900
        CALL ICSTTS
        ITBTS = ITBTS + 1
900   CONTINUE
C
C     DEBUG OUTPUT FOR TIMESTEP
C
      DUM1 = DIAM * 1.E6
      DPOLD = DUM1
      TPOLD = TLIQ
      IF(PRTLIN.AND.INJOUT(3).EQ.1)WRITE(8,600)II,JI,KI,ICNT2,TIME
     1 ,XPOLD,YPOLD,ZPOLD,UPOLD,VPOLD,WPOLD,TLIQ,DUM1,UGAS,VGAS,WGAS
600   FORMAT(' ',3I3,I4,E10.3,2F6.3,F6.1,3F7.2,F7.1,F8.2,3F7.2)
C
      RETURN
      END
C -------------------------------------------------------------------
```

```
      WPNEW = WPOLD + DRAGTH * DTIME - DUM3 + GRAVZ*DTIME
C
C     UPDATE GAS VELOCITY AT NEW POSITION
C
      UGAS = UBDY(II.JI,KI)
     1          + (UBDY(II+1,JI,KI) - UBDY(II,JI,KI))
     2            *(XPNEW - XBDY(II)) / (XBDY(II+1) - XBDY(II))
C
      VGAS = VBDY(II.JI,KI)
     1          + (VBDY(II,JI+1,KI) - VBDY(II,JI,KI))
     2            *(YPNEW - YBDY(JI)) / (YBDY(JI+1) - YBDY(JI))
C
      I1 = IY - JLAYER
      DUM2 = 1.
      IF(JI.GT.I1) DUM2 = ( R(IY) - YPNEW ) / BLAYER
      IF(JI.LE.JFORCE) GOTO 450
        DUM3 = CFREE(II,JI,KI)       * DUM2 / YPNEW
        DUM4 = CFREE(II,JI,KI+1) * DUM2 / YPNEW
450   CONTINUE
      IF(JI.GT.JFORCE) GOTO 460
        DUM3 = CFORCE(II,JI,KI)  * DUM2 * YPNEW
        DUM4 = CFORCE(II,JI,KI+1)* DUM2 * YPNEW
460   CONTINUE
      WGAS = DUM3 + (DUM4-DUM3)
     1                  * (ZPNEW - ZBDY(KI)) / (ZBDY(KI+1)-ZBDY(KI))
C
C     UPDATE DROPLET TEMPERATURE AND DIAMETER
C
C        ETAS ACCOUNTS FOR EFFECT OF DROPLET SPACING ON BURNING RATE
C
      DUMO = DINIT / SPACE
      ETAS = 1 - DUMO + DUMO**2 - DUMO**3 + DUMO**4 - DUMO**5 + DUMO**6
      IF(DUMO.GT.0.5) ETAS = 0.62
      IF(DUMO.GT.0.7) ETAS = 0.55
      IF(DUMO.GT.0.9) ETAS = 0.50
      IF(IDUM.EQ.2) ETAS = 1.0
      IF(INJOUT(5).EQ.6) ETAS = 1.0
C
C     CASE WHERE DROP IS BOILING
C
      IF(.NOT.BOIL) GOTO 500
        CBOIL = 8. * TCONDG(II,JI,KI) / RHOLIQ / CPGAS(II,JI,KI)
     1     * ALOG (1. + TRANSNO)
        DUM2 = DIAM*DIAM - ETAS * CBOIL * (1. + 0.23 * RENOLD**0.5)
     1       * DTIME
        DUM3 = DUM2 /DINIT /DINIT
        IF(DUM3.GT.1.E-12) GOTO 510
          WRITE(6,570)
          WRITE(7,570)
          WRITE(8,570)
          XPOLD = XPNEW
          YPOLD = YPNEW
          ZPOLD = ZPNEW
          UPOLD = UPNEW
          VPOLD = VPNEW
```

```
C        ETAE ACCOUNTS FOR EFFECT OF EVAPORATION ON DRAG
C
      ETAE=1.0
      IF (BOIL) ETAE = 1./(1. + TRANSNO)
C
      IF(INJOUT(5).EQ.7) ETAE = 1.0
C
      CDPL = CD * ETAE
      CDPD = CD1 * ETAE
      UDIF = UPOLD - UGAS
      VDIF  = VPOLD - VGAS
      WDIF = WPOLD - WGAS
      VDX = VPOLD * SIN(ZPOLD*3.14159/180.) +
     1      WPOLD * COS(ZPOLD * 3.14159/180.)
      VDY = VPOLD*COS(ZPOLD*3.14159/180.)-WPOLD*SIN(ZPOLD*3.14159/180.)
      VDZ = UPOLD
      VRX = VDIF*SIN(ZPOLD*3.14159/180.)+WDIF*COS(ZPOLD*3.14159/180.)
      VRY = VDIF*COS(ZPOLD*3.14159/180.)-WDIF*SIN(ZPOLD*3.14159/180.)
      VRZ = UDIF
C
      VRPL = (VRX * VDX + VRY * VDY + VRZ * VDZ) / VDT
C
      VRPLX = VRPL * VDX / VDT
      VRPLY = VRPL * VDY / VDT
      VRPLZ = VRPL * VDZ / VDT
C
      VRPDX = VRX - VRPLX
      VRPDY = VRY - VRPLY
      VRPDZ = VRZ - VRPLZ
C
      DUM1 = 0.75 * DENS(SUMASS,TEMP(II,JI,KI))/RHOLIQ/DIAM
C
C     OPTION TO SET DRAG = 0
C
      DRAGX = 0.0
      DRAGY = 0.0
      DRAGZ = 0.0
      IF(INJOUT(5).EQ.2) GO TO 400
      IF(INJOUT(5).EQ.3) GO TO 400
C
      DRAGX = -DUM1 * (CDPL*VRPLX*ABS(VRPLX) + CDPD*VRPDX*ABS(VRPDX))
      DRAGY = -DUM1 * (CDPL*VRPLY*ABS(VRPLY) + CDPD*VRPDY*ABS(VRPDY))
      DRAGZ = -DUM1 * (CDPL*VRPLZ*ABS(VRPLZ) + CDPD*VRPDZ*ABS(VRPDZ))
C
400   CONTINUE
C
      DRAGR = DRAGX*SIN(ZPOLD*PI/180.) + DRAGY*COS(ZPOLD*PI/180.)
      DRAGTH = DRAGX*COS(ZPOLD*PI/180.) - DRAGY*SIN(ZPOLD*PI/180.)
C
      UPNEW = UPOLD + DRAGZ * DTIME + GRAVX * DTIME
      DUM2  = 0.
      IF(YPOLD.GT.1.E-10) DUM2 = WPOLD**2 /YPOLD * DTIME
      VPNEW = VPOLD + DRAGR * DTIME + DUM2 + GRAVY*DTIME
      DUM3  = 0.
      IF(YPOLD.GT.1.E-10) DUM3 = VPOLD * WPOLD / YPOLD *DTIME
```

```
370         CONTINUE
            IF(DTIME.GE.1.E22) DTIME = OLDDT
360     CONTINUE
C
C                UPDATE DROPLET VELOCITY AT NEW POSITION
C                  (CDRE IS DRAG COEFF X REYNOLD NUMBER)
C
C           ALLOWANCE FOR GRAVITY
C
        GRAVX =  0.
        GRAVY =  0.
        GRAVZ =  0.
        IF (INJOUT(5).EQ.1) GO TO 364
        IF (INJOUT(5).EQ.3) GO TO 364
        GRAVX =  0.
        GRAVY = -9.81 * SIN (ZPOLD)
        GRAVZ = -9.81 * COS (ZPOLD)
C
364     CONTINUE
C
        RENOLD = DIAM*DENS(SUMASS,TEMP(II,JI,KI))/DVISCG(II,JI,KI)
       1       *((UPOLD-UGAS)**2 + (VPOLD-VGAS)**2 + (WPOLD-WGAS)**2 )**0.5
C
        IF(RENOLD.LE.80) CD1 = 27. * RENOLD**(-0.84)
        IF(RENOLD.GT.80.AND.RENOLD.LT.1.E4)
       1          CD1 = 0.271 * RENOLD**(0.217)
        IF(RENOLD.GE.1.E4) CD1 = 2.
C
C ADJUST DRAG FOR CLOSELY SPACED DROPLETS
C
        VMAG=((UPOLD-UGAS)**2+(VPOLD-VGAS)**2+(WPOLD-WGAS)**2)**0.5
        DRPVEL = (UPINIT**2 + VPINIT**2 + WPINIT**2) **0.5
        VDT = (UPOLD**2 + VPOLD**2 + WPOLD**2) **0.5
        SPACE = VDT * SPACIN / VINIT1
        IF(SPACE.LT.DIAM) SPACE = DIAM
        CD2= 0.755/RENOLD + 34.8 * RENOLD**(-1.009)*(SPACE/DIAM-1.)
        CD = (CD1 **(-0.7072) + CD2 **(-0.7072)) ** (-1./0.7072)
C
C       OPTION TO SET CD = CD OF ISOLATED DROP
C
        IF(INJOUT(5).EQ.4) CD = CD1
C
        CDRE = CD * RENOLD
C
C            TRANSFER NUMBER
C
        IF(IDUM.EQ.2) GO TO 700
        TRANSNO = (CPGAS(II,JI,KI) * (TEMP(II,JI,KI)-TLIQ) + HCOMLQ *
       1             FO2 / AFMRAT) / LHELIQ
        GO TO 710
700     CONTINUE
        IF(INPTYP(7).EQ.0) TRANSNO = FO2 / AFMRAT
        IF(INPTYP(7).EQ.1) TRANSNO = TRNO
710     CONTINUE
C
```

```
C     UPDATE DROP POSITION
C
      XPNEW = XPOLD + UPOLD*DTIME
      DUM1 = XBDY(II+1) + 1.0E-8
      IF(XPNEW.LT.DUM1) GOTO 300
          IINEW = II + 1
          DTIME = (XBDY(II+1) - XPOLD) /UPOLD
          XPNEW = XBDY(II+1)
300   CONTINUE
      DUM2 = XBDY(II) - 1.0E-8
      IF(XPNEW.GT.DUM2) GOTO 310
          IINEW = II - 1
          DTIME = (XBDY(II) - XPOLD) /UPOLD
          XPNEW = XBDY(II)
310   CONTINUE
C
      YPNEW = YPOLD + VPOLD*DTIME
      DUM3 = YBDY(JI+1) + 1.0E-8
      IF(YPNEW.LT.DUM3) GOTO 320
          JINEW = JI + 1
          DTIME = (YBDY(JI+1) - YPOLD) /VPOLD
          YPNEW = YBDY(JI+1)
320   CONTINUE
      DUM4 = YBDY(JI) - 1.0E-8
      IF(YPNEW.GT.DUM4) GOTO 330
          JINEW = JI - 1
          DTIME = (YBDY(JI) - YPOLD) /VPOLD
          YPNEW = YBDY(JI)
330   CONTINUE
C
      ZPNEW = ZPOLD
      IF(YPOLD.GT.1.E-10)
     1          ZPNEW = ZPOLD + WPOLD*DTIME /YPOLD * 180. /PI
      DUM5 = ZBDY(KI+1) + 1.0E-8
      IF(ZPNEW.LT.DUM5) GOTO 340
          KINEW = KI + 1
          DTIME = (ZBDY(KI+1)-ZPOLD)*PI/180. *YPOLD/WPOLD
          ZPNEW = ZBDY(KI+1)
340   CONTINUE
      DUM6 = ZBDY(KI) - 1.0E-8
      IF(ZPNEW.GT.DUM6) GOTO 350
          KINEW = KI - 1
          DTIME = (ZBDY(KI)-ZPOLD)*PI/180. *YPOLD/WPOLD
          ZPNEW = ZBDY(KI)
350   CONTINUE
C
C     CHECK FOR NEGATIVE OR HUGE TIMESTEPS NEAR BOUNDARY
C         (NEGATIVE TIMESTEP MEANS XPOLD WAS ACTUALLY IN NEW ZONE)
C         (HUGE TIMESTEP MEANS DROPLET VELOCITY VERY SMALL)
C
      IF(II.EQ.IINEW.AND.JI.EQ.JINEW.AND.KI.EQ.KINEW) GOTO 360
          IF(DTIME.GE.0.0) GOTO 370
            DTIME = OLDDT
            GETOUT = .TRUE.
            RETURN
      COMMON/SWRLCB/
     1       CFORCE(25,15,6), CFREE(25,15,6)
     2       ,BLAYER, RFORCE, SWIRL , TOTLEN, JLAYER, JFORCE
C
      COMMON/GASCB/
     1       CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
     2      ,FO2   , FN2   , FCO2  , FH2O
C
      COMMON/DROPCB/
     1       XPOLD, YPOLD, ZPOLD, UPOLD, VPOLD, WPOLD, DRPVEL
     2      ,XPINIT, YPINIT, ZPINIT, UPINIT, VPINIT, WPINIT
     3      ,RNDNUM, SPACIN, C, SPACE, IT, LOD, VINIT1
     4     , DPOLD, TPOLD, DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/NOZCB/
     1      XNOZ,YNOZ,ZNOZ
     2      ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
C     CONSTANT DATA
C
      DATA PI/3.14159/
C
C     DENSITY (KG M**-3), IDEAL GAS AT 1 ATM
C           (SUMASS IS GMOLES PER KG OF GAS MIXTURE)
C
      DENS(SUMASS,TEMPER) = 273./(SUMASS*0.0224*TEMPER)
C
C     OUTPUT LOGIC
C
      PRTLIN = .FALSE.
      IF(ICNT2.LE.NPRT1)     PRTLIN = .TRUE.
      IF(MOD(ICNT2,NPRT2).EQ.0) PRTLIN = .TRUE.
      IF(INJOUT(3).EQ.0)     PRTLIN = .FALSE.
C
      I1 = IX * IY * IZ
      IF(NPRT1.GT.I1) I1 = NPRT1
      IF(ICNT1.GT.I1)                  PRTLIN = .FALSE.
C
C     ADJUST TIMESTEP FOR EARLY PART OF ZONE
C
      DTIME = DTSAV
      IF(ICNT2.LE.NRAMP.AND.ICNT1.EQ.1)
     1       DTIME = DTSAV*FLOAT(ICNT2)/FLOAT(NRAMP)
C
C     ADJUST TIMESTEP FOR EVAPORATION
C
      DUMO = DIAM/DINIT
      DTIME = DTIME * (DUMO**2)
C
C     ADJUST TIMESTEP FOR CARBON BURNOUT PHASE
C
      IF(DIAM.GT.DINIT3) GO TO 200
      IF(DTIME.LT.0.0001) DTIME = 0.0001
  200 CONTINUE
C
```

```
         (filename:  DROP3D5.FOR)
      SUBROUTINE ICSMOV
C
C     Modified from DRPMOV by Mark Sheldon for EER, 5/1/85
C
C     PURPOSE:
C         "ICSMOV" stands for:
C         "Incineration Cylindrical 3-d model,
C           Subroutine for droplet MOVement"
C
      REAL     NUSELT, LOD
      REAL     LHELIQ, LHELIQ1, LHELIQ2
      INTEGER          TIMAX , DSTRIB
      LOGICAL*1    COMPND(40,20), CASE(60) , INCASE
      LOGICAL          BOIL    , CNVRG , GETOUT, PRTLIN, CYL
C
      COMMON/DIMCB/
     1         IX     , IY     , IZ     , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/LIQCB/
     1         TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4, DRT3I
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1         ZSAFE , DSAFE , TSAFE , ESAFE , TOL1
     2        ,NDROP , MAXSTP, NRAMP
C
      COMMON/PRTCB/
     1         CASE   , INCASE(80)     , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/MOVECB/
     1         DTIME , DTSAV , OLDDT , TIME   , PATH   , DIAM
     2        ,UGAS  , VGAS  , WGAS  , IINEW , JINEW , KINEW
     3        ,ICNT1 , ICNT2 , PRANDT, BOIL   , CNVRG , GETOUT
     4       , ITBTS
C
      COMMON/INPUT/
     1               V(25,15,5),    TEMP(25,15,5)
     2        ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC   , NPART
     3        ,II     , JI     , KI     , NCMPND, COMPND, JRAND
     4       , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/BDYCB/
     1         XL(25)      , XBDY(26)   , UBDY(26,15,5), UBDY1(26,15,5)
     2        ,R(15)       , YBDY(16)   , VBDY(25,16,5), VBDY1(25,16,5)
     3        ,DTHETA(5) , ZBDY(6)    , WBDY(25,15,6), WBDY1(25,15,6)
     4        ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
```

```
            WPOLD = WPNEW
            TIME    = TIME + DTIME
            DIAM = 0.
            GETOUT = .TRUE.
            RETURN
510       CONTINUE
          DIAM = DUM2**0.5
          TLNEW = TLIQ
C
C     CASE WHERE DROP TEMPERATURE IS CHANGING
C
500   CONTINUE
      IF(BOIL) GOTO 550
          NUSELT = 2. + 0.6 * (RENOLD**0.5) * (PRANDT**(1./3.))
          DUM3   = 6. *NUSELT *TCONDG(II,JI,KI)
     1                /RHOLIQ /DIAM /DIAM /CPLIQ
          TLNEW  = TEMP(II,JI,KI)
     1               - (TEMP(II,JI,KI)-TLIQ) * EXP(-DUM3 * DTIME)
C
C     CASE WHERE DROP STARTS BOILING DURING STEP (STARTS TO SHRINK TOO)
C
      IF(TLNEW.LT.TBOIL) GOTO 550
          DUM4 = DTIME - (1./DUM3)
     1          *ALOG((TEMP(II,JI,KI)-TLIQ)/(TEMP(II,JI,KI)-TBOIL))
          CBOIL = 8. * TCONDG(II,JI,KI) / RHOLIQ / CPGAS(II,JI,KI)
     1      * ALOG(1. + TRANSNO)
          DUM2 = (DIAM*DIAM - ETAS*CBOIL*(1.+0.23*RENOLD**0.5)*DUM4)
          DUM3 = DUM2 /DINIT /DINIT
          IF(DUM3.GT.1.E-12) GOTO 560
            WRITE(6,570)
            WRITE(7,570)
            WRITE(8,570)
570         FORMAT(1X,'DROP ASSUMED EVAPORATED WHEN 1.E-6'
     1                 ,' OF INITIAL DIAMETER')
            XPOLD = XPNEW
            YPOLD = YPNEW
            ZPOLD = ZPNEW
            UPOLD = UPNEW
            VPOLD = VPNEW
            WPOLD = WPNEW
            TIME    = TIME + DTIME
            DIAM = 0.
            GETOUT = .TRUE.
            RETURN
560       CONTINUE
          DIAM = DUM2**0.5
          TLNEW = TBOIL
          BOIL = .TRUE.
         WRITE(7,605) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
         WRITE(8,605) TIME,DIAM,XPNEW,YPNEW,ZPNEW,TLNEW
605      FORMAT(/ ' DROP STARTS TO BOIL AT T (SEC) = ',E10.3,
     1          ' AND D (M) = ',E10.3/ ' X (M) = ',F7.4,' Y (M) = ',
     2         F7.4,' Z (DEG) = ',F7.1,' T (K) = ',F7.1/)
C
C     TEST FOR VELOCITY CONVERGENCE
```

(filename: DROP3D6.FOR)

```
C
C       LABELS FOR AXES
C
        DIM(IX) = DUMNAM(1)
        DIM(IY) = DUMNAM(2)
        DIM(IZ) = DUMNAM(3)
C
C       FIND MAX AND MIN ORDER OF MAGNITUDE OF ARRAY ELEMENTS
C
        MAXPOW = 0
        MINPOW = 0
        DO 300 K=1,MZ
        DO 300 J=1,MY
        DO 300 I=1,MX
            IPOW = 0
            DUM1 = ABS(ARDUM(I,J,K))
            DUM2 = DUM1 * 10.**(15 + IABS(IPOW)) - .01
            IF(DUM2.LT.0.00000000)GOTO 300
320         CONTINUE
            IF(DUM1.LT.10.) GOTO 330
              DUM1 = DUM1 * 0.1
              IPOW = IPOW + 1
330         CONTINUE
            IF(DUM1.GE.1.)      GOTO 340
              DUM1 = DUM1 * 10.
              IPOW = IPOW - 1
340         CONTINUE
            IF(DUM1.GE.10.)GOTO 320
            IF(DUM1.LT.1.) GOTO 330
C
            IF(LATER) GOTO 350
              MAXPOW = IPOW
              MINPOW = IPOW
              LATER  = .TRUE.
350         CONTINUE
C
            IF(IPOW.GT.MAXPOW) MAXPOW = IPOW
            IF(IPOW.LT.MINPOW) MINPOW = IPOW
300     CONTINUE
C
C       CHECK MAX SPREAD OF MAGNITUDE IN ARRAY
C
        IOUT = 1
        IDUM1= MDEC + 1
        IDUM2= MAXPOW - MINPOW
        IF(IDUM2.GT.IDUM1) IOUT = 2
C
C       NORMALIZE ARRAY
C
        IF(IOUT.EQ.2)GOTO 400
            DO 410 K=1,MZ
            DO 410 J=1,MY
            DO 410 I=1,MX
              ARDUM(I,J,K) = ARDUM(I,J,K) * 0.100000**(MAXPOW)
410         CONTINUE
```

```
  140         CONTINUE
  130       CONTINUE
  100   CONTINUE
C
        IF(IX.NE.2) GOTO 150
            IF(IY.NE.1) GOTO 160
              IZ = 3
              MX = NY
              MY = NX
              MZ = NZ
              DO 170 K=1,NZ
              DO 170 J=1,NY
              DO 170 I=1,NX
                ARDUM(J,I,K) = ARRAY(I,J,K)
  170         CONTINUE
  160       CONTINUE
            IF(IY.NE.3) GOTO 180
              IZ = 1
              MX = NZ
              MY = NX
              MZ = NY
              DO 190 K=1,NZ
              DO 190 J=1,NY
              DO 190 I=1,NX
                ARDUM(K,I,J) = ARRAY(I,J,K)
  190         CONTINUE
  180       CONTINUE
  150   CONTINUE
C
        IF(IX.NE.3) GOTO 200
            IF(IY.NE.1) GOTO 210
              IZ = 2
              MX = NY
              MY = NZ
              MZ = NX
              DO 220 K=1,NZ
              DO 220 J=1,NY
              DO 220 I=1,NX
                ARDUM(J,K,I) = ARRAY(I,J,K)
  220         CONTINUE
  210       CONTINUE
            IF(IY.NE.2) GOTO 230
              IZ = 1
              MX = NZ               20 I
              MY = NY
              MZ = NX
              DO 240 K=1,NZ
              DO 240 J=1,NY
              DO 240 I=1,NX
              ARDUM(K,J,I) = ARRAY(I,J,K)
  240         CONTINUE
  230       CONTINUE
  200   CONTINUE
        WRITE (8,201) MX,MY,MZ
  201   FORMAT(5X,'MX = ',I2,' MY = ',I2,' MZ = ',I2)
```

```
 330  FORMAT(1X,I2,1X,3I3,17I4)
 340  CONTINUE
      N = N + 20
      NP = NP + 20
      IF(N.GT.NXMAX) GO TO 350
      GO TO 310
C
 350  RETURN
      END
C     ---------------------------------------------------------------
      SUBROUTINE ARRPRT(ARRAY,NX,NY,NZ,IX,IY,NAME)
C
C     Written by Mark Sheldon for EER, 5/2/85
C
C     PURPOSE:      ARRPRT ("ARRay PRinTout") outputs a 3-d array
C                   (up to 20X20X20) to a file.
C
C     LOCAL VARIABLES
C
      REAL          ARRAY(NX,NY,NZ),ARDUM(26,20,20)
      LOGICAL       LATER
      CHARACTER*1 NAME(40),DIM(3), DUMNAM(3)
C
C     INITIALIZATIONS
C
C      DATA DUMNAM/'I','J','K'/
      DUMNAM(1) = 'I'
      DUMNAM(2) = 'J'
      DUMNAM(3) = 'K'
      NDEC  = 3
      LATER = .FALSE.
C
C     STORE INPUT ARRAY IN DUMMY ARRAY TO BE MANIPULATED
C
      IF(IX.NE.1) GOTO 100
         IF(IY.NE.2) GOTO 110
           IZ = 3
           MX = NX
           MY = NY
           MZ = NZ
           DO 120 K=1,NZ
           DO 120 J=1,NY
           DO 120 I=1,NX
             ARDUM(I,J,K) = ARRAY(I,J,K)
120        CONTINUE
110      CONTINUE
         IF(IY.NE.3) GOTO 130
           IZ = 2
           MX = NX
           MY = NZ
           MZ = NY
           DO 140 K=1,NZ
           DO 140 J=1,NY
           DO 140 I=1,NX
             ARDUM(I,K,J) = ARRAY(I,J,K)
      WRITE(7,140)XPINIT,YPINIT,ZPINIT
140   FORMAT(4X,'INITIAL POSITION: X (M)  :',F8.3
     1            ,'  Y (M)  :',F8.3,'  Z (DEG) :',F8.3)
C
      WRITE(7,150)UPINIT,VPINIT,WPINIT
150   FORMAT(4X,'INITIAL VELOCITY: U (M/S):',F8.3
     1            ,'  V (M/S):',F8.3,'  W (M/S) :',F8.3,/)
C
      WRITE (7,160) VINIT1,LOD,SPACIN
160   FORMAT(4X,'INITIAL TOTAL VELOCITY (M/S) :',F10.3/4X,
     1          'INITIAL SPACING : ',F9.3,' DROPLET DIAMETERS'/4X,
     2          'INITIAL SPACING BETWEEN DROPLETS (M) : ',E10.3)
C
      WRITE(7,170) TIMAX,XMEAN,YMEAN,ZMEAN
170   FORMAT(/2X,'THE DATA CONTAINS ',I4,' DATA POINTS, WITH THE ',
     1 'AVERAGE EVAPORATION POINT'/2X,'LOCATED AT (',F5.3,',',F5.3,
     2 ',',F7.3,').')
      WRITE(7,180) STDVX,STDVY,STDVZ
180   FORMAT (2X,'THE STANDARD DEVIATIONS ARE (',F5.3,',',F5.3,
     1              ',',F5.1,')')
      WRITE(7,190) XMIN,XMAX,YMIN,YMAX,ZMIN,ZMAX
190   FORMAT (2X,'THE RANGES IN ALL DIRECTIONS ARE ',
     1       'X: (',F5.3,'-',F5.3,')'/36X,'Y: (',F5.3,'-',F5.3,')'/
     2    36X,'Z: (',F5.1,'-',F5.1,')')
      WRITE(7,200) NXGRID,NYGRID,XFINAL,YFINAL
200   FORMAT(2X,'IN THIS GRID, GRID POINTS X = ',I2,' AND Y = ',
     1    I2,/2X,'CORRESPOND'
     2    ,' TO THE PHYSICAL LOCATION (',F5.3,',',F5.3,').')
C
      N = 1
      NP = 20
      WRITE(7,230)
 230  FORMAT(/25X,'DISTRIBUTION OF DROPLET EVAPORATION')
 240  WRITE(7,250) (J,J=N,NP)
 250  FORMAT(/3X,'X',3I3,17I4,/2X,'Y')
      DO 280 J = 1,NYMAX
      WRITE(7,260) J,(DSTRIB(I,J),I=N,NP)
 260  FORMAT(1X,I2,1X,3I3,17I4)
      DO 270 I = N,NP
      DST2(I,J) = INT(FLOAT(DSTRIB(I,J)) * 10. /FLOAT(DSTMAX))
 270  CONTINUE
 280  CONTINUE
      N = N + 20
      NP = NP + 20
      IF (N.GT.NXMAX) GO TO 290
      GO TO 240
C
 290  N = 1
      NP = 20
      WRITE(7,300)
 300  FORMAT(/20X,'NORMALIZED DISTRIBUTION DENSITY RANGING FROM 1 - 10')
 310  WRITE(7,320) (J,J=N,NP)
 320  FORMAT(/3X,'X',3I3,17I4,/2X,'Y')
      DO 340 J = 1,NYMAX
      WRITE(7,330) J,(DST2(I,J),I=N,NP)
      END
C-----------------------------------------------------------------------
      SUBROUTINE ICPINJ
C
C     Modified from INJPRT by Mark Sheldon for EER, 5/2/85
C
C     PURPOSE:
C         "ICPINJ" stands for:
C         "Incineration Cylindrical 3-d model,
C           Printout for subroutine "ICSINJ""
C
            LOGICAL*1   CASE(60), INCASE
            INTEGER   TIMAX,  DSTMAX, DST2(50,20), DSTRIB
            REAL     LOD
            INTEGER DST(50,20)
C
      COMMON/DIMCB/
     1          IX     , IY     , IZ     , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/INPUT/
     1            V(25,15,5),   TEMP(25,15,5)
     2         ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3         ,II     , JI     , KI     , NCMPND, COMPND
     4       , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNO
C
      COMMON/PRTCB/
     1          CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2         ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/PRINT/
     1          DSTRIB(50,20), DSTMAX, NXMAX, NYMAX, XMEAN, YMEAN, ZMEAN
     2          , XFINAL, YFINAL, NXGRID, NYGRID, STDVX, STDVY, STDVZ
     3          , XMAX, YMAX, ZMAX, XMIN, YMIN, ZMIN
C
      COMMON/DROPCB/
     1          XPOLD, YPOLD, ZPOLD, UPOLD, VPOLD, WPOLD, DRPVEL
     2         ,XPINIT, YPINIT, ZPINIT, UPINIT, VPINIT, WPINIT
     3         ,RNDNUM, SPACIN, C, SPACE, IT, LOD, VINIT1
     4       , DPOLD, TPOLD, DINIT, DINIT2, DINIT3, DINIT4
C
C     OUTPUT -      PRINT INITIAL CONDITIONS AND STATISTICS
C
      WRITE(7,100)
100   FORMAT(1X,/,1X,'INJECTION RESULTS:',/)
C
      WRITE(7,105)(CASE(I),I=1,60)
105   FORMAT(1X,60A1)
      WRITE(7,110)(INCASE(I),I=1,70)
110   FORMAT(1X,70A1)
      WRITE(7,120)
120   FORMAT(1X,/,1X,'DROPLET INITIAL CONDITIONS:')
C
      WRITE(7,130)DINIT
130   FORMAT(4X,'INITIAL DROP DIAMETER (M) = ',E10.3)
C
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      COMMON/DROPCB/
     1          XPOLD, YPOLD, ZPOLD, UPOLD, VPOLD, WPOLD, DRPVEL
     2        ,XPINIT, YPINIT, ZPINIT, UPINIT, VPINIT, WPINIT
     3        ,RNDNUM, SPACIN, C, SPACE, IT, LOD, VINIT1
     4      , DPOLD, TPOLD, DINIT, DINIT2, DINIT3, DINIT4
C
      COMMON/NOZCB/
     1        XNOZ,YNOZ,ZNOZ
     2        ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
C     DEBUG OUTPUT HEADER
C
      WRITE(8,110)(CASE(I),I=1,60)
110   FORMAT('1',/,1X,60A1)
C
      WRITE(8,120)(INCASE(I),I=1,70)
120   FORMAT(1X,70A1)
C
      WRITE(8,220)
220   FORMAT(1X,/,1X,'DROPLET INITIAL CONDITIONS:')
C
      WRITE(8,230)DINIT
230   FORMAT(4X,'INITIAL DROP DIAMETER (M) = ',E10.3)
C
      WRITE(8,240)XPINIT,YPINIT,ZPINIT
240   FORMAT(4X,'INITIAL POSITION: X (M)  =',F8.3
     1           ,'  Y (M)  =',F8.3,'  Z (DEG) =',F8.3)
C
      WRITE(8,250)UPINIT,VPINIT,WPINIT
250   FORMAT(4X,'INITIAL VELOCITY: U (M/S)=',F8.3
     1           ,'  V (M/S)=',F8.3,'  W (M/S) =',F8.3,/)
C
      WRITE (8,255) DRPVEL,LOD,SPACIN
255   FORMAT(4X,'INITIAL TOTAL VELOCITY (M/S) =',F10.3/4X,
     1         'INITIAL SPACING = ',F9.3,' DROPLET DIAMETERS'/4X,
     2         'INITIAL SPACING BETWEEN DROPLETS (M)  = ',E10.3)
C
      WRITE(8,290)
290   FORMAT(1X,'DROP TIME HISTORY:',/)
C
      WRITE(8,300)
300   FORMAT(' ','          STEP                POSITION      '
     1              ,'   VELOCITY (M/S)')
C
      WRITE(8,310)
310   FORMAT(' ','          # IN   TIME   AXIAL RADIAL ANGLE'
     1              ,' AXIAL RADIAL TANGENT  TEMP DIAMETER'
     2              ,'  UGAS   VGAS   WGAS ')
C
          WRITE(8,320)
320   FORMAT(' ',' II JI KI ZONE   (SEC)   X(M)  Y(M) Z(DEG)'
     1              ,'  U      V      W      (K) (MICRON)'
     2              ,' (M/S)  (M/S)  (M/S) ')
C
      RETURN
      COMMON/INPUT/
     1              V(25,15,5),   TEMP(25,15,5)
     2        ,SUMASS, TIMAX , TEMAX , TEMIN , TAUC  , NPART
     3        ,II    , JI    , KI    , NCMPND, COMPND
     4       , XSIGMA, YSIGMA, ZSIGMA, TBTS, TRNG
C
      COMMON/GASCB/
     1         CPGAS(25,15,5) , DVISCG(25,15,5), TCONDG(25,15,5)
     2        ,F02   , FN2   , FC02  , FH20
C
C     OUTPUT HEADER
C
      WRITE(8,200)(INCASE(I),I=1,70)
200   FORMAT(1X,70A1)
C
      WRITE(8,220)F02,FNFN2,FC02,FH20
220   FORMAT(1X,/,1X,'MASS FRACTIONS:',/,1X
     1        ,'02=',F6.4,3X,'N2=',F6.4,3X,'C02=',F6.4,3X,'H20=',F6.4)
C
C     INPUT ARRAYS
C
      CALL ARRPRT(TEMP       ,IX     ,IY     ,IZ     ,1,2
     1,'ZONE TEMPERATURE (K)                    ')
C
C     OUTPUT ARRAYS
C
      CALL ARRPRT(CPGAS ,IX     ,IY     ,IZ     ,1,2
     1,'ZONE HEAT CAPACITY (M*M/S/S/K)          ')
C
      CALL ARRPRT(DVISCG,IX     ,IY     ,IZ     ,1,2
     1,'ZONE DYNAMIC VISCOSITY (KG/M/S)         ')
C
      CALL ARRPRT(TCONDG,IX     ,IY     ,IZ     ,1,2
     1,'ZONE THERMAL CONDUCTIVITY (KG/S/S/S/K) ')
C
      RETURN
      END
C----------------------------------------------------------------------
      SUBROUTINE ICPSPR
C
C     Modified from DRPPRT by Mark Sheldon for EER, 5/3/85
C
C     PURPOSE:
C         "ICPSPR" stands for:
C         "Incineration Cylindrical 3-d model,
C           Printout subroutine for "ICSSPR"
C
           LOGICAL*1   CASE(60), INCASE
           INTEGER  DSTRIB
           REAL           LOD
C
      COMMON/PRTCB/
     1         CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
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C
720   CONTINUE
C
      WRITE(8.750)XNOZ,YNOZ,ZNOZ
750   FORMAT(4X,'INJECTION COORDINATES(M): X:'
     1            ,F6.3,' Y:',F6.3,' Z:',F8.3)
C
      WRITE(8,800)
800   FORMAT(1X,/,1X,'PROGRAM PARAMETERS:')
C
      WRITE(8,810) NDROP
810   FORMAT(4X,'NUMBER OF DROPLETS INJECTED :',I8)
C
      WRITE(8,820)MAXSTP
820   FORMAT(4X,'MAXIMUM NUMBER OF STEPS IN LOOP, MAXSTP = ',I10)
C
      WRITE(8,830) NRAMP
830   FORMAT(4X,'TIMESTEP SIZE INCREASED OVER ',I4
     1            ,' STEPS, 1ST ZONE')
C
      WRITE(8,840)ZSAFE
840   FORMAT(4X,'SAFETY FACTOR FOR ZONE TRAVERSE, ZSAFE = ',F7.3)
C
      WRITE(8,850)DSAFE
850   FORMAT(4X,'SAFETY FACTOR FOR DRAG TIMESTEP, DSAFE = ',F7.3)
C
      WRITE(8,860)TSAFE
860   FORMAT(4X,'SAFETY FACTOR FOR TEMP TIMESTEP, TSAFE = ',F7.3)
C
      WRITE(8,870)ESAFE
870   FORMAT(4X,'SAFETY FACTOR FOR EVAP TIMESTEP, ESAFE = ',F7.3,/)
C
      RETURN
      END
C ------------------------------------------------------------------
      SUBROUTINE ICPGAS
C
C     Modified from GASPRT by Mark Sheldon for EER, 5/3/85
C
C     PURPOSE:
C         "ICPGAS" stands for:
C         "Incineration Cylindrical 3-d model,
C           Printout subroutine for "ICSGAS""
C
          REAL*4 DUMAR(25,15)
          INTEGER     TIMAX
          LOGICAL*1   COMPND(40,20), CASE(60), INCASE
C
      COMMON/DIMCB/
     1         IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/PRTCB/
     1                   CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
```

```
390         CONTINUE
300      CONTINUE
C
         CALL ARRPRT(UBDY1 ,IY     ,IXPLUS,IZ     ,2,1
       1,'AXIAL  GAS VELOCITY AT ZONE BDY, M/S    ')
C
         CALL ARRPRT(VBDY1 ,IX     ,IYPLUS,IZ     ,1,2
       1,'RADIAL GAS VELOCITY AT ZONE BDY, M/S    ')
C
         CALL ARRPRT(ROTBDY,IX     ,IY     ,IZPLUS,1,2
       1,'ROTATIONAL GAS VEL AT ZONE BDY, M/S     ')
C
         CALL ARRPRT(WBDY1 ,IX     ,IY     ,IZPLUS,1,2
       1,'TANGENTIAL GAS VEL AT ZONE BDY, M/S     ')
C
         CALL ARRPRT(CFREE ,IX     ,IY     ,IZPLUS,1,2
       1,'CONSTANT FOR FREE VORTEX, M**2 /S       ')
C
         CALL ARRPRT(CFORCE,IX     ,IY     ,IZPLUS,1,2
       1,'CONSTANT FOR FORCED VORTEX, S**-1       ')
C
        WRITE(8,510)
510     FORMAT(1X,/,1X,'SWIRL PARAMETERS:')
C
        WRITE(8,520) SWIRL
520     FORMAT(4X,'SWIRL NUMBER=',F10.4)
C
        WRITE(8,530) TOTLEN
530     FORMAT(4X,'TOTAL INCINERATOR LENGTH=',F10.4)
C
        WRITE(8,540) JFORCE, JLAYER
540     FORMAT(4X,'FORCED VORTEX IN INNER',I3,' ZONES (WGAS GOES AS R)'
       1         ,/,4X,'FREE VORTEX IN REMAINING ZONES (WGAS GOES AS 1/R)'
       2         ,/,4X,'BOUNDARY LAYER IN OUTER',I3,' ZONES')
C
        WRITE(8,600)
600     FORMAT(1X,/,1X,'INITIAL DROPLET PROPERTIES:')
C
        WRITE(8,620)TLIQ
620     FORMAT(4X,'INITIAL DROP TEMP     (K) = ',F7.1)
C
        WRITE(8,630)TBOIL
630     FORMAT(4X,'LIQUID BOILING TEMP   (K) = ',F7.1)
C
        WRITE(8,640)RHOLIQ
640     FORMAT(4X,'LIQUID DENSITY (KG M**-3) = ',E10.3)
C
        WRITE(8,650)CPLIQ
650     FORMAT(4X,'LIQUID HEAT CAPACITY (M**2 S**-2 K**-1) = ',E10.3)
C
        WRITE(8,660)LHELIQ
660     FORMAT(4X,'LATENT HEAT OF EVAP. (M**2 S**-2)        = ',E10.3,/)
C
        WRITE(8,740)AFMRAT
740     FORMAT(4X,'AIR/FUEL MASS RATIO=',F7.4)
```

```
C
      WRITE(8,240)(INCASE(I),I=1,70)
  240 FORMAT(1X,70A1,/)
C
      WRITE(8,260)IX,IY,IZ
  260 FORMAT(1X,'SOLUTION GRID: I=',I3,' AXIAL BY J=',I3
     1           ,' RADIAL BY K=',I3,' AZIMUTHAL ZONES',/)
C
      WRITE(8,270)
  270 FORMAT(1X,'ZONE BOUNDARY LOCATIONS:')
C
      WRITE(8,280)
  280 FORMAT(4X,'ZONE I,J,K IS BETWEEN XBDY(I) AND XBDY(I+1),ETC.')
C
      I1 = IXPLUS
      IF(IYPLUS.GT.I1) I1 = IYPLUS
      IF(IZPLUS.GT.I1) I1 = IZPLUS
      DO 300 I = 1,I1
         IF(I.LE.IXPLUS.AND.I.LE.IYPLUS.AND.I.LE.IZPLUS)
     1     WRITE(8,310)I,XBDY(I),I,YBDY(I),I,ZBDY(I)
  310      FORMAT(4X,'XBDY(',I3,') =',F8.4
     1              ,5X,'YBDY(',I3,') =',F8.4
     2              ,5X,'ZBDY(',I3,') =',F9.4)
C
         IF(I.LE.IXPLUS) GOTO 320
           IF(I.LE.IYPLUS.AND.I.LE.IZPLUS)
     1       WRITE(8,330)I,YBDY(I),I,ZBDY(I)
  330        FORMAT(4X,25X,'YBDY(',I3,') =',F8.4
     1                     ,5X,'ZBDY(',I3,') =',F9.4)
C
           IF(I.GT.IYPLUS)
     1       WRITE(8,340)I,ZBDY(I)
  340        FORMAT(4X,25X,25X,'ZBDY(',I3,') =',F9.4)
C
           IF(I.GT.IZPLUS)
     1       WRITE(8,350)I,YBDY(I)
  350        FORMAT(4X,25X,'YBDY(',I3,') =',F8.4)
  320    CONTINUE
C
         IF(I.LE.IYPLUS) GOTO 360
           IF(I.LE.IXPLUS.AND.I.LE.IZPLUS)
     1       WRITE(8,370)I,XBDY(I),I,ZBDY(I)
  370        FORMAT(4X,'XBDY(',I3,') =',F8.4
     1         ,5X,25X,'ZBDY(',I3,') =',F9.4)
C
           IF(I.GT.IZPLUS)
     1       WRITE(8,380)I,XBDY(I)
  380        FORMAT(4X,'XBDY(',I3,') =',F8.4)
  360    CONTINUE
C
         IF(I.LE.IZPLUS) GOTO 390
           IF(I.LE.IXPLUS.AND.I.LE.IYPLUS)
     2       WRITE(8,392)I,XBDY(I),I,YBDY(I)
  392        FORMAT(4X,'XBDY(',I3,') =',F8.4
     1                ,5X,'YBDY(',I3,') =',F8.4)
```

```
      SUBROUTINE ICPSET
C
C     Modified from SETPRT by Mark Sheldon for EER, 5/2/85
C
C     PURPOSE:
C         "ICPSET" stands for:
C         "Incineration Cylindrical 3-d model,
C           Printout from subroutine for SETup (ICSSET)"
C
            LOGICAL*1   CASE(60), INCASE
          REAL         LHELIQ, LHELIQ1, LHELIQ2
C
      COMMON/DIMCB/
     1          IX    , IY    , IZ    , IXPLUS, IYPLUS, IZPLUS
C
      COMMON/LIQCB/
     1          TLIQ, TINIT, IDUM
     2        , TBOIL, TBL1, TBL2, TBL3
     3        , DRT2, DRT3, DRT4, DRT3I
     4        , RHOLIQ, RHOLIQ1, RHOLIQ2, RHOLIQ3
     5        , LHELIQ, LHELIQ1, LHELIQ2
     6        , CPLIQ, CPLIQ1, CPLIQ2, CPLIQ3
     7        , HCOMLQ, HCOMLQ1, HCOMLQ2
     8        , AFMRAT, AFMRAT1, AFMRAT2, AFMRAT3
C
      COMMON/PARMCB/
     1          ZSAFE , DSAFE , TSAFE , ESAFE , TOL1
     2        ,NDROP , MAXSTP, NRAMP
C
      COMMON/PRTCB/
     1          CASE  , INCASE(80)    , INJOUT(10), INPTYP(10)
     2        ,NPRT1 , NPRT2 , NPRT3
C
      COMMON/BDYCB/
     1          XL(25)    , XBDY(26)   , UBDY(26,15,5), UBDY1(26,15,5)
     2        ,R(15)      , YBDY(16)   , VBDY(25,16,5), VBDY1(25,16,5)
     3        ,DTHETA(5)  , ZBDY(6)    , WBDY(25,15,6), WBDY1(25,15,6)
     4        ,ROTBDY(25,15,6), TWALL(25,15,5) , CYL
C
      COMMON/SWRLCB/
     1          CFORCE(25,15,6), CFREE(25,15,6)
     2        ,BLAYER, RFORCE, SWIRL , TOTLEN, JLAYER, JFORCE
C
      COMMON/NOZCB/
     1        XNOZ,YNOZ,ZNOZ
     2        ,UPCOMP,VPCOMP,WPCOMP,UNOZ
C
C     DEBUG OUTPUT HEADER
C
      WRITE(8,200)
200   FORMAT('1',/,' ','*** DROPLET INJECTION MODEL ***',/)
C
      WRITE(8,220)(CASE(I),I=1,60)
220   FORMAT(1X,60A1)
```

END
DATE
FILMED
6-20-88
NTIS